COMMUNITY-SCALE BIOSAND FILTER PILOT PROJECT IN CAMBODIA

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A

PROJECT REPORT

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By

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Abstract

Clean water is a basic human necessity that is essential for the health of all population, yet 700 million people worldwide lack access to this vital resource, particularly in developing countries like Cambodia. This results in high incidences of water-borne illnesses due to the use of contaminated sources and is a burden that prevents people from leading productive lives. Slow sand filtration, both on the municipal level and the household level, is a low-cost technology that has been implemented around the world to address this problem, yet biosand filtration has not been widely implemented on a community level due to the lack of tested, effective filter technology. In this pilot project, a community-scale biosand filter was designed, constructed and tested to determine if it can meet the water needs of a small floating village in the Siem Reap Province of Cambodia. With the collaboration of local partner organizations, this project demonstrated that community-scale biosand filters are a viable and effective solution to rural clean water challenges in Cambodia.

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Acknowledgments

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Chapter 1 Introduction

Clean drinking water is a basic human necessity and right which 700 million people in the world lack, with the vast majority of these people living in poor, rural areas. Cambodia is at the forefront of clean water issues and solutions. Biosand filters have been shown to be effective, affordable and sustainable solutions to cleaning water at the point-of-use. More biosand filters have been implemented in Cambodia than any country in the world (Liang, Sobsey, & Stauber, 2010).

Trailblazer Foundation (TF), a non-governmental organization (NGO) operating in Siem Reap, Cambodia, has delivered over 3,000 biosand filters (BSFs) in the Siem Reap Province since 2003, and is the community partner for this biosand filter pilot project. After conversations with the field director and project director/founder, it was decided that the most worthwhile project for TF would be design and construction of a pilot community-scale biosand filter. To date, Trailblazer has only attempted to build one large-capacity BSF. This BSF, designed by the P3 BioSand Bag Filter organization, was initially a success. Constructed out of a large canvas/plastic "bag" that could hold approximately 1000 liters, it provided adequate flow for a larger number of families in the local floating village of Peam Ta Ou, with good water quality test results. However, the biosand bag filter is currently not in use and the staff of TF has concerns about the durability, sustainability and cost versus benefit of this design.

However, Trailblazer Foundation still feels that the basic idea of a large-capacity community BSF has merit. There has been limited to no peer-reviewed literature on the design or efficacy of large-scale biosand filter other than informal testing conducted by P3

Biosand Bag Filter. However, during the course of this project, the principal investigator made contact with Samaritan's Purse, an NGO operating in Cambodia that is currently designing and implementing community-scale biosand filters, which they call "intermittently operated slow sand filters." Their poster submitted to the 2015 Water and Health Conference (Cantwell, 2015) was the first peer-reviewed presentation of this type of biosand filter that has been discovered to date. During this project, Samaritan's Purse was consulted on the design of a large biosand filter (LBSF).

Despite some known technical challenges, it was considered valuable and feasible to design and construct a large-scale plastic 700-liter biosand filter as a pilot for testing. The project provided value to TF as a potential working model and further contributed to the body of scientific knowledge in the biosand filter field.

Chapter 2 Background

2.1 The water problem

Over 700 million people in the world lack access to a basic human right and necessity: clean, potable water. Despite this dire fact, incredible progress has been made to bring clean water to those in need. The Millennium Developmental Goals (MDG) on drinking water set an ambitious target of halving the proportion of the world's population without sustainable access to clean water. The target water coverage was set at 88% of the world's population. The goal was met in 2010 and drinking water coverage stands at 91% today (World Health Organization [WHO], 2015). Since 1990, 2.3 billion people have gained access to improved sources of drinking water and 116 countries have met the MDG target for water (WHO & United Nations Children's Fund [UNICEF], 2014).

Yet challenges remain. There is still a large disparity of coverage between rural and urban populations. Of the 748 million people who lack access to clean drinking water sources, most are poor and marginalized, 90% live in rural areas, and almost a quarter of these people rely on untreated surface water (WHO & UNICEF, 2014). Not only is this population the most vulnerable, they are the hardest to reach. And due to climate change, it is estimated that by 2025 half of the world's population will live in water-stressed areas (WHO, 2015).

It is well established that drinking contaminated water can transmit diseases such as cholera, dysentery, typhoid and polio. It is estimated to cause 502,000 diarrheal deaths each year, with a large portion of these being children under the age of five (WHO, 2015). A lack of clean water also contributes to water-washed diseases, such as skin and eye infections, which are caused by lack of clean water for washing. Hennessy et al. (2008)

showed that rural regions with lower levels of on-premise clean water had significantly higher hospitalization rates for pneumonia, influenza, and skin or soft tissue infections than did regions with better clean water service.

The human cost of unimproved water goes further: consuming unsafe water has adverse effects on school attendance and economic development as water-borne illnesses lead to high rates of missed workdays, school absenteeism, and increased expenditures on health care (WHO, 2015). When people spend less time and effort collecting water from improved sources, they can be more productive in other ways.

2.2 Country profile: Cambodia

It is an exciting time for Cambodia, and there is new sense of optimism. To put the public health situation in context, it is important to understand the country's tumultuous history. For 2,000 years Cambodia's civilization was influenced by India and China. The classical age of the Khmer Empire period lasted from the 9th to the 15th century, and was an era marked by construction of massive imperial complexes. Over one million people lived in Angkor, which is now famous for the Angkor Wat temple. After a 400-year period of decline, Cambodia experienced French colonization and then independence during a tumultuous 20th century. The late 1960's through the 1970's was an era of unparalleled devastation, which included widespread bombing of Cambodia during the Vietnam War. Unexploded ordinance riddles the countryside to this day. In 1975 a civil war ended, but a new reign of terror- *the Khmer Rouge*- took control. Over two million people lost their lives during that time and millions of more landmines were laid (Cambodia Tribunal Monitor, n.d.).

In the 1980's, Cambodia was essentially cut off from much of the world. United Nations (UN)-sponsored elections in 1993 helped restore order under a coalition government (Central Intelligence Agency [CIA], n.d.). Khmer Rouge influence continued until 1999 when all of its leaders had defected, had been arrested, or had died. Democratic stability took a step forward with truly representative elections in 2002; stability remains to this day. However, the brutal fallout of the last 40 years remains: destroyed infrastructure, deaths and disabilities from landlines to this day and older generations still bear the psychic trauma (Cambodia Tribunal Monitor, n.d.). The public health of the country has suffered.

"Fear not the future, weep not for the past." Cambodian proverb (Chandler, n.d.).

Cambodia has emerged from its dark shadows to make remarkable economic and health gains over the last decade. The country is inhabited by 15.7 million people, of which 90% are of Khmer ethnicity. The Cambodian GDP grew at an average annual rate of over 8% between 2000 and 2010 and over 7% since 2011 (CIA, n.d.). From 1990 to 2013 the under-five mortality rate decreased from 118 to 38 per 1,000 live births, and the maternal mortality rate decreased almost *ten-fold*: from 1,200 to 170 per 100,000 live births (WHO, 2015).

Despite the progress, many developmental challenges remain. As of 2012, approximately 2.66 million people live on less than $1.20 per day, and are inhibited by endemic corruption, limited educational and employment opportunities (particularly in rural areas), and high income inequality. Thirty-seven percent of Cambodian children under the age of 5 suffer from chronic malnutrition. Because of these challenges, the international aid community has stepped in, and almost a third of the government budget comes from donor assistance (CIA, n.d.).

Cambodia is comprised of 24 provinces. The economic and health challenges are pronounced in rural provinces, which lack basic infrastructure. According to the National Institute of Statistics (NIS) et al (2011), rural areas have an under-five mortality rate of 75 per 1,000, while in urban areas it is 20 per 1,000. Part of the discrepancy is due to lack of access to clean water. For rural populations, only 49% have clean water access on premise, and for 41% it is less than 30 minutes away. In 2014 UNICEF Cambodia's spokesman stated: "The government has many priorities in terms of development such as infrastructure and other areas, so sometime it hasn't been focused on clean water and sanitation." (Savbory & Yun, 2014).

2.3 Site project profile: Siem Reap

The province in which this project took place is Siem Reap (Figure 2.1), the flat central floodplain home to approximately 900,000 people. The defining geographic feature of Siem Reap is Tonle Sap, the largest freshwater lake in Southeast Asia, and one that once supported the Angkor Empire. The lake feeds the Tonle Sap

Figure 2.1. Map of Siem Reap province in Cambodia

River, which travels 120 km to meet the Mekong River. The lake is known for its extraordinary seasonal variation in water level and volume. A unique characteristic of the system is the yearly flooding of the Mekong, which causes a backflow up the Tonle Sap River. During this wet season the water depth in the lake rises up to 10 meters, while quadrupling in surface area and extending over vast floodplains (Keskinen, 2006).

Due to the seasonal fluctuation, a large portion of the population live on floating villages, which ebb and flow with the yearly tide. This way of life presents unique challenges including access to clean, potable water. One of these floating villages is Peam Ta Ou, where Trailblazer Foundation has implemented a large biosand bag filter project.

The economy in the province is heavily supported by tourism, due to the presence of the United Nations Educational, Scientific and Cultural Organization World Heritage Angkor temples on the outskirt of Siem Reap town. The result has been a boomtown economy in Siem Reap. The tourism industry has grown rapidly with tourists reaching around 4.5 million visitors in 2014 (CIA, n.d.).

2.4 Water quality and access in Cambodia

Cambodia is a prime case study of the successes and remaining challenges of providing access to clean water. While 37% of the population gained access to clean water between 2000 and 2012, seventeen percent of the population is still using untreated surface water as a primary drinking source (WHO & UNICEF, 2014).

During the dry season from November to April, more than 40% of Cambodians use unimproved drinking water sources. Water treatment is wide practiced at the household level. The most common method is boiling, used by 60% of the population, followed by a variety of other methods. Only 2% use household filtration (ceramic, sand, or other), and up to 30% do not treat drinking water at all (Liang, Sobsey, & Stauber, 2010).

The geography and weather of Cambodia offer further unique challenges that require novel solutions to clean water deficiencies. Flood plains can restrict access to clean water for some, and groundwater can be difficult and costly to obtain or it is contaminated. For example, in the Mekong region, groundwater can be hazardous due to the high levels of arsenic and other chemical contaminants. As a result, biologically contaminated surface and shallow water sources are often used as alternatives to arsenic-contaminated deep wells (Liang, Sobsey, & Stauber, 2010).

Water quality standards in Cambodia are set by the Ministry of Mines and Energy (MIME). These published Drinking Water Quality Standards (MIME, 2004) conform to WHO guidelines, with the exception of arsenic, which has a higher maximum limit in Cambodia. This is due to the fact that it would be difficult and costly to enforce the WHO standard of 10 ug/l in Cambodia, and the potential health risk of ingesting water with arsenic levels between 10 and 50 ug/l is low relative to the risk posed by water with bacteriological contamination, which should be the priority according to MIME (2004).

Water quality at the point-of-use often has a high level of bacteriological contamination, which can be measured by the presence of total coliforms. Common in nature, coliforms often inhabit the digestive tracks and feces of warm-blooded mammals, and include both fecal and non-fecal bacteria from humans, animals, and decayed organic matter. All coliforms can occur in human feces, but they can also exist in natural settings outside the human body. Since their presence indicates contamination of a water supply by an outside source, they are a useful parameter for drinking water quality (Environmental Protection Agency [EPA], n.d.). Total coliforms are able to ferment lactose at either 35 or 37°C within 24-48 hours (MIME, 2004).

Fecal coliforms are a subset of total coliform bacteria that are more specifically associated with fecal contamination from warm-blooded animals. Also known as thermotolerant coliforms, they can ferment lactose at 44.5°C during analysis (MIME, 2004). *Escherichia coli (E. coli)* is a species of fecal coliform bacteria that is specific to fecal material from humans and other warm-blooded animals. *E. coli* has traditionally been used as a primary indicator to monitor drinking-water quality, but testing thermotolerant coliforms can be used as an alternative to *E. coli* in many circumstances. Water intended for human consumption should contain no fecal indicator organisms (WHO, 2011).

The WHO (2011) recommends a minimum volume of 7.5 liters per capita per day to "provide sufficient water for hydration and incorporation into food for most people under most conditions." This does not include water for personal and domestic hygiene, which are also important for health. Having access to approximately 20 liters of water per day per person would still be considered "basic" access according to WHO, with a resulting "high" public health risk from poor hygiene (WHO, 2011).

2.5 Household water treatment solutions in Cambodia

A primary goal to meet the MDG targets on potable water is to increase access to reliable, safe piped water for the majority of the world's population. However, due to the high capital costs of piped supply systems, universal safe piped water is likely decades away for many developing regions. Until this goal can be met, the WHO and others have called for targeted, interim approaches to meet drinking water needs. Effective household water treatment and safe storage (HWTS) methods are some of the most promising of these approaches, and can significantly improve the microbiological quality of drinking water (Clasen, 2009).

Although HWTS is not new, its potential as a focused public health intervention strategy is emerging. The most common HWTS methods include boiling, solar disinfection, ceramic filters, purification sachets and biosand filters. In 2007, the combined efforts of HWTS (exclusive of boiling) produced approximately 15.5 billion liters of treated water worldwide. Among various filtration options with proven microbiological performance, only ceramic and biosand filters have been actively promoted as HWTS options for lower-income populations (Clasen, 2009).

Biosand filters were developed as an innovation of traditional slow-sand filters (SSFs), which have been used to treat drinking water on a municipal level for 200 years (Young-Rojanschi & Madramootoo, 2014). The concept of slow sand filtration is very basic: by passing water through fine sand at a slow rate, chemical and biological contaminants are trapped by the sand and predated on by natural organisms in the sand, and the water is purified.

Dr. David Manz of the University of Calgary developed the biosand filter in 1991. In 2001 the Centre for Affordable Water and Sanitation Technology (CAWST) was founded to provide professional services, training, technical support and other resources for the distribution of the filter in developing countries (CAWST, n.d.). Approximately 650,000 biosand filters have been implemented in over 55 countries, serving more than four million people (Ngai et al., 2014). Cambodia is at the forefront of this technology: there are more BSFs in Cambodia than anywhere in the world. Part of the reason for this is because the BSF water treatment technology is particularly suited for Cambodia. There is no dearth of water in Cambodia- only contaminated water that needs to be treated. The BSF's microbiological performance is comparable to other household water treatment interventions, with the additional advantages of it not being prone to breakage or needing replacement parts, it can be constructed with locally sourced materials, it is relatively small, and it does not require constant delivery of untreated water (Liang, Sobsey, & Stauber, 2010).

The quantity of filtered water from one BSF unit is approximately 60 liters per day. This is obtained when the filter is filled with five or six batches of water per day using a bucket or jerry can to fill 10-12 liters per fill (12 liters is the recommended maximum per fill). For a household of six people this is 10 liters per person per day.

2.6 Household biosand filter history and research

While new plastic BSF designs have come on the market, the traditional BSF is essentially a square concrete holding tank about 1 meter tall and 300 cm wide (See Figure 2.2). Concrete BSFs are ideally prepared at a facility that has access to the basic raw resources and parts, but is close enough to the installation site due to their weight of approximately 80-100 kg. They are produced in steel molds that cost between $250-$900 each (depending on the local market), and each mold can produce 1-2 filters per day at total cost of $12-$40 each (Clasen, 2009). In Cambodia, this cost has been estimated to be $15.50 on average (Liang, Sobsey, & Stauber, 2010).

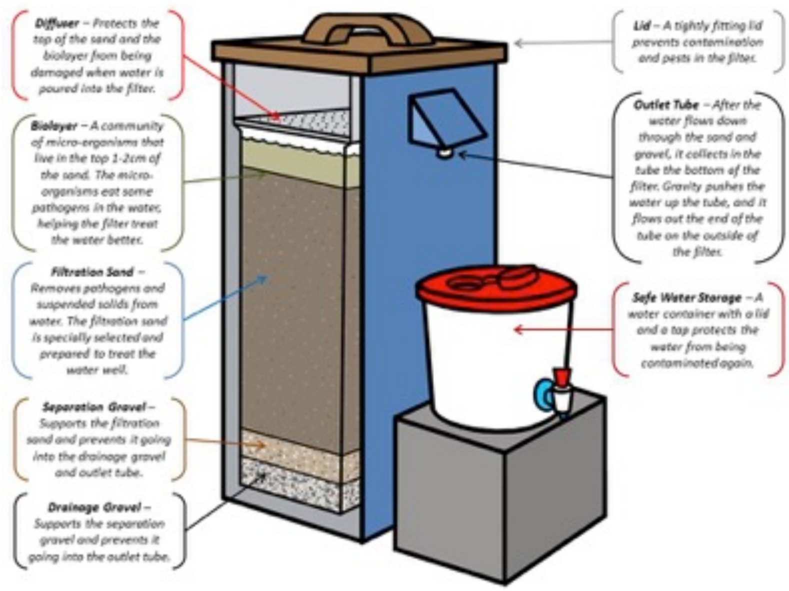


Figure 2.2. Diagram of a household BSF. Diagram courtesy of CAWST.

At the installation site, the BSF is filled with layers of specially prepared sand and gravel. The sand removes pathogens and suspended solids from contaminated drinking water as it passes though the layers with the mechanisms of natural death, trapping, inactivation and adsorption. The sand bed depth should be approximately 0.55 meters (CAWST, 2012). The top 1-2 centimeters of the sand forms a biolayer (also known as a “schmutzdecke”) of bacteria and other microorganisms. The biolayer eats many of the pathogens in the water, improving the water quality (CAWST, n.d.). Since the biolayer is an active part of the purification process, it is important to keep it “alive.”

At the bottom of the filter a gravel layer allows for drainage into the outlet pipe. At the top of the filter, above the water level, is a diffuser plate, generally a steel plate with holes in it, which allows water to be poured into the BSF without disrupting the biolayer.

The BSF operates by pouring untreated water onto the diffuser plate, which slowly flows down the length of the filter bed by gravity. A bottom outlet pipe is directed upwards into a standpipe, which has an outlet near the top. Water is pushed up to the outlet by hydrostatic pressure. The typical initial flow rate of water through the BSF is 0.4 liters per minute, making it possible to produce a maximum of 24 liters in an hour (flow rate will decrease as standing head decreases). The location of the outlet nozzle establishes pressure equilibrium, ensuring that a 5 cm layer standing layer of water remains above the sand surface at all times, including periods between the additions of untreated water.

There are a few technical aspects that require attention and proper training to ensure the proper function of the BSF. The biolayer must mature (or "ripen") to improve its predation characteristics. Adding too much water can result in less microbial activity, which is why intermittent filling of the BSF is suggested. Fittingly, the intermittent nature of the technology makes it more suitable for household applications. Attention needs to be paid to the biolayer, as it will eventually become clogged, which requires regular cleaning to increase continuity of performance. A relatively simple "clean in place" technique minimizes the need for total sand bed removal, which does simplify maintenance (Liang, Sobsey, & Stauber, 2010).

The normal model of distribution, usually administered and funded by NGOs, requires filter recipients to participate in training and assist in the manufacture, transport and installation of the biosand filter. This 'sweat equity' may be combined with a small fee to ensure that the recipients are invested while allowing the technology to reach the most poor and disadvantaged (Clasen, 2009).

Although many NGOs have conducted internal testing and evaluations, fewer independent evaluations using scientific methods have evaluated BSF performance, particularly in the field. Most studies indicate it is a technology of clear value and promise, although there is still a great need for further study and testing. The CAWST claims that BSFs can remove up to 100% of helminthes and protozoa, up to 98.5% of bacteria, up to 95% of iron, 70-99% of viruses, while improving water turbidity by up to 95%. Like other filters, it cannot remove dissolved contaminants including salt, arsenic or fluoride. However, modifications such as adding rusty nails to the diffuser layer can remove arsenic from the water (CAWST, n.d.), through the process of iron hydroxide adsorption.

Laboratory studies have supported the claim that BSFs improve water quality. One rigorous laboratory study of 18 biosand filters over 10 weeks found combined results of a bacterial removal rate of 96%, virus reduction of 71% and turbidity removal of 89% (Jenkins et al, 2011). Elliot et al. (2008) studied BSF performance on biolayer ripening time and the volume of water poured into the filter daily. Under conditions of 30 days ripening, the BSF reduced *E. coli* by 99% on average, and echovirus 12 by 99% on average, with a bacteriophage reduction of 70%.

Field studies have also showed similarly promising results. A randomized control trial of the plastic biosand filter in rural Ghana showed a mean reduction of 97% of *E.*

coli and 67% of turbidity. The longitudinal prevalence ratio for diarrhea, comparing households that received the plastic BSF to controls was 0.40 (95% CI: 0.05, 0.8), suggesting an overall diarrheal reduction of 60% (Stauber et al, 2012). A cross-sectional study of 336 BSF households in Cambodia concluded that BSF treatment resulted in a 95% reduction of *E. coli* and an 82% reduction in turbidity of untreated source water. There was a 47% reduction of diarrheal disease compared to control households that did not have BSFs (Liang, Sobsey, & Stauber, 2010).

A longitudinal randomized control trial on plastic BSF performance in Honduras highlights some of the challenges of conducting studies in remote field conditions. While this rigorous study showed that the incidence of diarrheal disease in children under five was reduced by approximately 45% (O.R.= 0.55, 95% C.I. = 0.28, 1.10), the finding was not statistically significant (Fabiszewski de Aceituno et al., 2012). Measuring and interpreting diarrheal disease incidence can be problematic. It can be difficult to ensure that respondents are sourcing all their water from BSF-treated sources, and it is reasonable to conclude this is particularly true for children under five. Incidences of diarrhea may have also been underreported because of participant fatigue or the difficulty for caretakers to remember disease events in the 7-day recall period (Fabiszewski de Aceituno et al., 2012).

The BSF intervention group in this study by Fabiszewski de Aceituno et al. (2012) also showed a 51% lower mean *E. coli* concentration than the control, which is much lower than what many other similar studies find. This could have been due to the fact that some of the samples from the control group were drinking water that had been treated with chlorine or by boiling. In addition, the intervention group samples included samples directly from the BSF and samples from stored BSF-water, which could have been re-contaminated.

In fact, the issues with safe storage water containers and re-contamination is a common problem. The Cambodia study noted that a significant portion of BSF treated and stored samples became re-contaminated after filtration, suggesting the need for additional training and education (Liang, Sobsey, & Stauber, 2010). Clasen (2009) notes that BSFs have shown somewhat less effective microbiological performance than other HWTS option, which could be in part due to storage recontamination.

The literature convincingly supports the efficacy of biosand filters. Due to the nascence of the technology, there is a great need for further research to further understand the biological mechanisms, drawbacks and needs for improvement for this relatively new technology.

In a scalability evaluation conducted by WHO, Clasen (2009) summarized the uptake of BSFs around the globe. A six-country evaluation of 600 households using biosand filters for at least 3 months concluded that 98% of all recipients used their filters regularly and 89% used them every day. Satisfaction was similarly high; in Haiti for example, all users reported liking the units, with 97% of the filters still functioning after 2.5 years and 92% of the units were still considered well maintained. In Kenya, 97% of users who purchased the filters 4 years before reported that they were "generally satisfied" (Clasen, 2009).

A cross-sectional study of 336 households in Cambodia found that 87% of the households were using the BSF at the time of the survey visit. Household still using the BSF had been using them from six months up to eight years. Of these households, they reported using an average of 46 liters of water per day from the BSF (Liang, Sobsey, & Stauber, 2010). Evidence shows that with the proper training and education, which leads to the proper maintenance, BSFs are a durable, reliable and sustainable point-of-use technology.

2.7 Site project partner: Trailblazer Foundation

Trailblazer Foundation (TF) is a community-based non-profit organization working in Siem Reap Province with the core activities of sustainable agriculture training and development, beneficiary aid (mosquito bednets, cook stoves, units) and clean water projects. Clean water projects are focused on biosand filter construction and dissemination and water well drilling. The foundation states that they "practice a sustainable, community-focused style of development, which is a low cost and long-term solution to alleviating poverty and increasing the quality of life in a sustainable manner" (Trailblazer Foundation, n.d.).

The mission of Trailblazer Foundation is:

> "To develop self-sustaining projects and programs that rely and depend upon local talent and skills; to provide opportunities for self-employment and economic independence; to reduce dependency on international aid; to promote world peace" (Trailblazer Foundation, n.d.).

The formation of the organization was inspired by a trip by Scott and Chris Coats when they first visited Cambodia while volunteering in Southeast Asia in 2002. They made it their goal to return to Cambodia to focus on assisting rural villages in Cambodia.

Trailblazer Foundation was incorporated as a 501(c)3 in 2004 and the Coats moved to Cambodia full-time in 2005 to begin their work. In Cambodia, TF is registered non-governmental organization with the Ministry of Interior.

After consulting with officials in the district of Angkor Thom, the village of Sras was identified as one of the poorest villages in the region, and the Coats began their work there. As of December 2013, TF had expanded to working directly in 52 villages, while partnering with other NGOs to work in six total districts (Trailblazer Foundation, n.d.)

The biosand filter project has become a pillar program of TF (see Figure 2.3). They installed 425 biosand filters in 2013, bringing the total to nearly 3,000 BSFs installed in total, providing clean water to over 100,000 people (Trailblazer Foundation, 2013).

Trailblazer Foundation is governed by a U.S.-based Board of Directors consisting of six volunteer directors, mostly based in Jackson Hole, Wyoming. The U.S. office has 3 staff: Executive Director Chris Coats, Project Director Scott Coats (both of whom spend extended periods in Cambodia), and an executive secretary. In Cambodia, the organization is run almost entirely by national staff, led by a field director, who oversees a national staff of 12 local Cambodians (Trailblazer Foundation, n.d.)

Figure 2.3. Biosand filters ready for delivery at Trailblazer Foundation.

2.8 Large-scale biosand filters: background and need

Trailblazer Foundation's biosand filter program has been successful, with a high uptake, user rate and life span of the units. However, the BSF program is not feasible for all villages in Siem Reap Province. One example of a community facing unique clean water challenges is the village of Peam Ta Ou, which is located at the headwaters of the Tonle Sap where it flows in and out of Tonle Sap Lake. Peam Ta Ou is a floating village: it is composed of floating homes that move with the seasonal tidal variation. There is no road to the village, and there is no clean water: villagers drink water from the Tonle Sap. The incidence of waterborne disease is high and since there is no doctor in the village, sick patients need to travel over an hour and half to the nearest clinic (Coats, personal communication, October 8, 2015).

The environment presents many challenges for clean water. Since biosand filters are heavy (80 kg+) and are designed to be stationary, they are not a viable solution for a floating village. The best solution to date has been the distribution of PUR® sachets for purification; however this solution is costly and unsustainable in the long-term.

The directors of Trailblazer Foundation came across a potentially novel solution. Biosand Bag Filter Limited Liability Corporation (LLC) designed a large-scale biosand filter out of lightweight materials that could be transported to remote sites. Capable of holding up to 5000 pounds of water and sand, the filter can be constructed on-site on a heavy-duty floating platform that can provide enough clean water for a small community, while being able to move during the seasonal fluctuations. This size of filter can serve a smaller population than a municipality slow sand filter can serve, but more than a household BSF.

The "P3 Biosand Bag" pilot filter was designed and tested by the founders of Biosand Bag Filter LLC (BBFL) in 2009. The primary component is the bag, which is made of a nylon canvas exterior with a plastic interior lining. The bag is supported by wooden vertical supports (see Figure 2.4). One major design difference is that in lieu of heavy gravel for drainage, the bottom of the biosand bag is layered with pieces of polyvinyl chloride (PVC) pipes drilled with small holes and fitted with a heavy-duty nylon "sleeve" supplied by BBFL. The PVC tubes provide structural support and drainage (while reducing weight), and the sleeve prevents sand from filtering through the holes.

Figure 2.4 Biosand bag filter construction. *Photo courtesy of Biosand Bag LLC.*

Biosand Bag Filter LLC reported the following results of testing in from October to November 2009, which were not verified by independent analysis:

- October: 2-log reduction in coliform bacteria for intervention versus control.
- November 7: total coliform results were not duplicated (unspecified results); *E. coli* reduced by 99.5%
- November 20: coliform results *were* duplicated (unspecified results); 100% reduction in *E. coli*

- November 30: 85% reduction in total coliform; 100% reduction in *E. coli*.

The testers theorize that variance in results may have resulted from changes in the ripening of the biolayer, which may have been in part due to the temperature fluctuations during that time of year, which was decreasing, with an average temperature of 48° F (9° C). The researchers noted that these colder temperatures do not mimic the conditions in most tropical and semi-tropical areas in which the filters would normally be implemented (Biosand Bag Filter LLC, n.d.).

While the results were not verified by independent analysis, the promise of the technology warranted a trial period in Cambodia. TF received a biosand bag kit from BBFL in 2013 and in June 2013 installed the filter in Peam Ta Ou. The installation took four days and involved building a platform and support structure made from locally sourced timber. After installation, the filter was filled with water from the Tonle Sap confluence using a small gasoline pump. Water was collected and tested after the initial flow-through. Due to the size of the filter, it took 40 days to get clear water; at this point water was again collected and tested at a local laboratory in Siem Reap.

Trailblazer reports that the water quality tests were encouraging and the filter functioned very well for six months in Peam Ta Ou (S. Coats, personal communication, October 15, 2015) After six months, the filter needed to be moved, hence it was disassembled. The plan was to move the filter to a floating platform that the village had constructed for this purpose. However, Trailblazer had some doubts about the sustainability of the product.

The hesitancy with the Biosand Bag filter came down to two issues: cost and durability. With a cost of over $1800 for the kit, plus the additional sand, timber support structure, labor and other costs, the Biosand Bag is about twice the cost of what TF would deem sustainable, especially considering that normal concrete BSF's cost less than $20 each to produce. The other issue was durability. While the product has an advertised life span of three years, the nature of the bag materials leads the TF project leaders to believe that it might be less durable due to the environmental conditions in Cambodia: high heat, humidity and solar radiation (S. Coats, personal communication, September 8, 2015). Hence, the large-scale BSF implementation was put on hold.

Despite the challenges of the Biosand Bag, the staff of Trailblazer Foundation still felt that a large BSF has merit. The output quality and quantity of the Biosand Bag Filter lead them to believe a similar, yet more durable and economical design would be appropriate. The village of Peam Ta Ou still has a floating platform for a large BSF that they spent considerable time and resources to construct. If Trailblazer finds that a large-scale (700L) biosand filter can be built at a target price point of less than $800, and it demonstrates effectiveness, they will potentially implement the large-scale BSF at the floating platform in Peam Ta Ou.

Figure 2.5. Floating platform in Peam Ta Ou

There is emerging interest in large-scale biosand filtration methods. During the course of this project, the CAWST put the principal investigator in contact with Samaritan's Purse, who are currently designing and implementing community-scale biosand filters using 1000L tanks that can produce up to 3,000 liters today, enough to serve very small villages or institutions like schools (Cantwell, 2015). In a poster presented at the 2015 Water and Health Conference in North Carolina in October (during this project), they reported similar encouraging results. Between 2012 and the end of 2015, Samaritan's Purse installed 170 of these 1000-liter filters in schools across Cambodia. In 2014 and 2015 they conducted water quality testing and found a mean *E. coli* removal rate of 97.8% across filters (n=66), which is a better removal rate than typically reported for household biosand filters and is consistent with 2-log removal in the literature for slow sand filters. They also reported a mean turbidity removal rate of 82% (Cantwell, 2015).

2.9 Rationale for a large biosand filter

A large BSF synthesizes the design and technologies of a traditional slow-sand filter (SSF) and the household BSF. To be used on a community level, the filter will produce approximately 3,000 liters per day. This type of filter can be called an "intermittently operated slow sand filter," or a "community scale biosand filter," or, as most often referred to in this project, a "large biosand filter" (LBSF).

There are key differences between the filter technologies. SSFs are large sand filters that have been historically used in municipal water treatment processes. Dr. Manz developed the small, concrete BSF to meet the needs of families in developing countries, and modified the design to meet those needs. A large biosand filter (LBSF) is a synthesis of both. The differences between the technologies are outlined in Table 2.1.

Table 2.1. Technical differences between SSFs, BSFs and LBSFs

Characteristic	Slow sand filter (SSF)	Biosand filter (BSF)	Large biosand filter (LBSF)
Output	Municipal-need levels	60 liters/day (family)	Community-need level (~3,000 liters/day)
Operating water flow	Continual flow	Intermittent flow (up to 4 fillings per 24 hours)	Continual with constant head
Residence (pause) times	None (continual flow)	Several times per day	None needed; only as required by user needs and water availability
Biolayer cleaning	Top ~1 cm of sand is removed approx. every 6 weeks	When clogged, top layer of sand is cleaned in place with minimal removal and disturbance	When clogged, top layer of sand is cleaned in place with minimal removal and disturbance
Standing water head (supernatant) level	One meter; kept at continuous flow	5 cm of minimal head between fillings	5 cm of minimal head between fillings
Filtration rate	0.1- 0.2 m^3/m^2/hour	0.4 m^3/m^2/hour → zero (avg. ~ 0.2)	0.2 m^3/m^2/hour (constant head)

The main difference between the systems is the amount of clean water that can be produced. A LBSF serves a much smaller population than a municipality slow sand filter serves, but much more than a household BSF. Recent LBSF have been constructed using 1000L tanks that can produce up to 3,000 liters today, enough to serve a very small village or an institution like a school (Cantwell, 2015).

While both SSFs and BSFs have functioning biolayers, there are important differences in schmutzdecke function/maintenance between the types of filters. In the SSF, the continuous flow of water provides oxygen to the biolayer of the SSF (Huisman & Wood, 1974). Manz developed the BSF so that it kept the schmutzdecke alive by ensuring that during non-flow (pause) conditions, a standing water (supernatant) level of no more than 5 cm ensured oxygen could permeate to the biolayer (The Concrete Filter, n.d.). While CAWST (2012) suggests “less water depth is better,” they also acknowledge that there is little real data on oxygen levels in the supernatant and lower layers. Recent studies have found that even with the reduced standing head of the BSF (5 cm), the top layers of the media may become anoxic during the residence period (Young-Rojanschi & Madramootoo, 2014).

Another key difference between SSFs and BSFs is the cleaning requirements of the biolayer. Cleaning a slow sand filter requires scraping off the top 1-2 cm of biolayer sand when the SSF becomes clogged. The water level must be lowered below the biolayer level, which requires special plumbing. There is also a considerable amount of labor that goes into the cleaning process, and the process of cleaning destroys the schmutzdecke (CAWST, n.d.). In a BSF, when the schmutzdecke gets clogged, methods can be used to clean the biolayer without removing sand and destroying the schmutzdecke. Jenkins et al. (2011) found that seven days after they disturbed the schmutzdecke during maintenance, there was no effect on virus removal and only a modest effect on bacterial removal, indicating the biolayer recovers rapidly from disruption.

Another major difference is continuous versus intermittent operation. Slow sand filters traditionally operate under continuous low-flow conditions, which give sufficient opportunity for the sand and biolayer to purify the water. Biosand filters, on the other hand, are used intermittently (CAWST, n.d.), which is more feasible for the household user. One benefit of intermittent use is that it increases residence time (or pause time). This is the amount of time the water resides in the sand between fillings, which allows for the sand layer to fulfill its functions of predation, adsorption, and starvation in purifying the residing water. In fact, a household BSF is most effective and efficient when operated intermittently and consistently, with pause periods between one and 48 hours. But if the pause period is extended for too long, the microorganisms will eventually consume all of the nutrients and pathogens and then eventually die off. This will reduce the removal efficiency of the filter when it is used again (CAWST, 2009).

A LBSF will be able to operate under continuous operation with a constant head, however it will also function properly with pause periods, because the 5 cm standing water level will maintain the biolayer. The user will determine the frequency of use. The constant head-controlled continual flow will be slow enough to allow for purification, as in an SSF. In an interesting experiment by Young-Rojanschi and Madramootoo (2014), small biosand filters were tested under continuous operation. They found that continuous operation of the filters resulted in significantly better reduction of *E. coli*, bacteriophage MS2, and turbidity.

Many other studies have shown that increasing the retention time of water in BSF reduces the amount of bacteria, viruses, and turbidity (Elliot et al, 2008; Jenkins et al., 2011, Tiwari et al., 2009). A LBSF will operate under "the best of both worlds," continual low-flow purification with residence times as needed by the user.

The final major difference between the systems is the maintenance of the filtration rate. The filtration rate is the maximum speed at which the water moves through the sand, and is measured in cubic meters per square meter per hour (m^3/m^2/hour). The filtration rate is also known as the hydraulic loading rate (HLR), and the terms may be used interchangeably. Continuous slow sand filters historically have operated at a constant filtration rate of 0.1 to 0.2 m^3/m^2/hour (CAWST, n.d.). These rates were historically seen in the operation of SSF in municipal treatment facilities like Amsterdam, London and Paris, where very good biological quality of water was achieved (Huisman & Wood, 1974). The household BSF is designed to operate at a maximum filtration rate of 0.4 m^3/m^2/hour (400 L/ m^2/hour), which decreases towards zero as the head decreases down to the standing water level. The average HLR for one load of water is approximately 0.2 m^3/m^2/hour- about the same as a municipal slow sand filter (CAWST, n.d.). The target rate is the maximum filtration rate of 0.4 m^3/m^2/hour, and is achieved when the BSF is first installed in the household with a 'clean bed' (Ngai & Baker, 2014).

A LBSF will maintain a 0.2 m^3/m^2/hour filtration rate- the same as a slow sand filter- through the use of a constant head device. In this design, a float valve maintains a constant hydraulic load. This approach has been recently employed in Ethiopia and Cambodia (D. Baker & R. Cantwell, personal communication, October 8-16, 2015). Unlike a SSF, this constant head LBSF can still be cleaned by hand using a "swirl and dump" wet harrowing technique, and it still maintains the biolayer oxygenation during pause periods with a standing head.

The design of a large-scale BSF reconciles all the technical differences between BSFs and SSFs. It is important to note that CAWST does not recommend the construction of large biosand filters. On their website, they address the issue succinctly:

> "A large 'community size' biosand filter will be very hard to clean, and it will probably be used too often (you still need one hour pause periods). It will probably not filter water as well as a standard biosand filter (the measurements of the biosand filter are very specific, and changing them correctly requires a lot of technical expertise). A 'community size' biosand filter is not a very practical idea, for all of these reasons, and others" (CAWST, n.d.).

However, CAWST does not provide any further evidence or rationale for these recommendations. Instead they recommend that many traditional concrete biosand filters be placed in a series to fulfill the water needs of a small community. Due to the weight of traditional concrete filters, placing many in a series on a floating platform would be infeasible. There is also the issue of maintaining and cleaning several filters at the same time.

After a review of the literature, no unsolvable technical challenges to constructing a larger BSF were identified. The main recommendation from CAWST (2012) was that any modifications to a BSF should ensure that the filtration rate is maintained at 0.2 m^3/m^2/hour. Achieving this is primarily dependent on having the proper sand characteristics and levels, which was not beyond the scope of this project.

Other concerns of CAWST (n.d.) are addressed in this project. For example, it is not anticipated that the filter will be "very hard to clean" if designed properly. The BBFL team showed that a large-scale filter can be designed to produce clean water in a controlled study, and TF replicated these results in the field. Samaritan's Purse demonstrated further positive results with 1000L biosand filters in the field in Cambodia (Cantwell, 2015). Whether or not large BSFs are efficacious and feasible warrants further study, which this project addressed.

Chapter 3 Project Goal and Objectives

Project Goal

The goal of this project was to design and construct a pilot large-scale biosand filter for Trailblazer Foundation, which operates in the Siem Reap Province of Cambodia. After construction, the filter was tested for flow, water quality, cost and general functionality to determine if it is effective and feasible to use as a functioning filter for a local floating village, and other communities as appropriate.

Project Objectives

The specific objectives for this project were as follows:

1. Design one large-capacity (700 liter) biosand filter using the scientific principles of BSF construction. Design specifications included materials that can be sourced locally in Cambodia, using techniques that can be easily replicated with local labor and tools.
2. Construction of one pilot large BSF filter on-site at Trailblazer Foundation according to the design specifications. During construction and testing qualitative data was collected on parameters including, but not limited to 1) feasibility of construction/installation, 2) ease of cleaning the biolayer, 3) ease of filling the filter on a daily basis, and 4) other maintenance issues. These data were analyzed in the results.
3. Analysis of the final cost of the pilot project to determine economic feasibility.
4. Water quality and flow was tested on a weekly basis up to six weeks to determine the effectiveness of the filter in purifying water versus a control.

Chapter 4 Methods

4.1 Study Design

The study design used quantitative and qualitative methodologies included the following types of analyses:

- Quantitative analysis to compare the water quality of the large-scale BSF versus the control,
- Quantitative analysis to determine the estimated cost-per-person for this method of water delivery.
- Qualitative analysis to explore themes in the observation notes regarding technical challenges and successes, needed modifications, anticipated user needs and issues

4.2 Project Area and Site Selection

The site project partner organization, Trailblazer Foundation, is based in Siem Reap town and has a service coverage radius of approximately 60 kilometers. Siem Reap province is one of two provinces in the country identified by the Cambodian Government and the World Food Program as significantly poor and food insecure (Trailblazer Foundation, 2013). Many of the provincial communities are in rural, un-served locations, including those that live in floating villages. People in these villages, and in many of the floodplain regions, are unable to access reliable sources of water including piped water and water wells. Due to this, the primary source of potable water for many comes from household water treatment methods.

Consultations with TF staff lead to the idea for this project proposal: constructing a large-scale BSF using a 700 L plastic water container that was sitting at the TF worksite. Since these types of water containers are widely available in Cambodia for less than $200 (generally used for clean water storage), the BSF would be an economical and scalable technology. TF signed a community partnership agreement with the principal investigator to move forward with the project on September 12, 2015 (see Appendix A).

The design and construction was conducted at a workshop on TF grounds, where concrete BSFs are constructed and other projects are implemented. Trailblazer staff assisted the principal investigator in the design and construction of the pilot BSF.

4.3.1 Development of the biosand filter design

To complete the large BSF design, a more extensive literature review, observations of local materials and building methods, consultations with experts in the field of biosand filter technology, and consultations with local experts on how local practices may influence design were included. Primary sources for design included the CAWST, which disseminates manuals on BSF design and construction, and moderates the on-line Biosand Filter Knowledge Base (CAWST, n.d.), an extensive online forum on BSF construction and research. Technical consultants at CAWST, which included prominent researchers in the field, were extensively consulted during this project. In addition, the NGO Samaritan's Purse, which is involved in BSF implementation in Cambodia, including, was also extensively consulted.

Literature research on BSF specifications and design were conducted using the University of Alaska Anchorage Consortium Library's online QuickSearch tool, which provides a single search box to find books and articles across most of the library's collections. It is powered by Summon, a web-scale discovery service from Serial Solutions. The search terms used included “biosand filter” and “intermittent slow sand filter.”

A preliminary literature review of QuickSearch in September 2015 yielded 158 journal article results for the search term “biosand filter.” Approximately half of these articles were specifically related to direct research on biosand filters. A significant portion of these were news-related or summaries of BSF studies. The remaining relevant articles were evaluations of BSF interventions or scientific research articles on the technical aspects of BSF functionality. Due to the fact that the field is still in its infancy, it is not surprising the search yields relatively few results. All of the relevant articles were reviewed for this project, with particular focus on the scientific aspects of BSF design including media layer depths, flow rates, residence times, biolayer maintenance, and other technical details.

Trailblazer Foundation staff provided technical consultation to help determine the best practices of designing and implementing the BSF to ensure cost-effectiveness, ease of implementation and the practicality of design.

Relevant literature review information is cited and referenced in this report. Descriptive notes were the instruments used to capture information from technical consultations (see Appendix B).

4.3.2 Construction of the biosand filter

Construction was guided by the final design of the large-scale biosand filter, which was designed according to the methods above. Descriptive notes were taken during the construction process as consultations were made or any modifications were needed based on information gleamed from direct observation (see Appendix B). Observational notes were taken on the functionality of the filter, including the overall feasibility of construction/installation, ease of filling, ease of cleaning the filter, and other issues observed including maintenance issues and potential barriers to the user.

4.3.3 Cost analysis of a 700-liter biosand filter

All materials costs were captured in a cost analysis Excel spreadsheet. The principal investigator and Trailblazer staff provided pro-bono labor for construction of the BSF. The initial goal was to capture man-hours of work to help calculate an estimate of real-world labor costs; however, after consulting TF management, it was determined that labor would be a negligible cost, due to the extreme low cost of labor in Cambodia. In addition, it would have been challenging to accurately capture hours worked due to the erratic nature of the hours spent on this pilot project by the principal investigator and TF staff.

4.3.4 Water-testing methods

Water quality was tested for the priority parameters (see Table 4.1) in small water supplies according to the guidelines stipulated by the Ministry of Mines and Energy (MIME) Cambodia Drinking Water Quality Standards (CDWQS).

Table 4.1. MIME (2004) parameters for small water supplies

Parameter	Maximum Value
pH	6.5-8.5
Turbidity	5 Nephelometric Turbidity Units (NTU)
Arsenic	0.05 mg/L
Iron	0.3 mg/L
Total Dissolved Solids (TDS)	800 mg/L
Thermotolerant Coliforms or *E. coli*	0 per 100 ml
Total coliforms*	0 per 100 ml

**Total coliforms are not listed by MIME as a priority parameter, but they are a general drinking water quality standard by MIME and WHO (MIME, 2004).*

Influent water for the BSF (experimental) and the control water were collected from the same pond water source near the Trailblazer Foundation worksite. The water source was selected using two parameters: 1) ability to maintain sufficient water quantities during the drier months of November and December, and 2) it contained sufficient bacteriological contamination so that the purification effectiveness of BSF could be properly tested. Parameter 1 was determined by consulting Trailblazer Foundation staff, and parameter 2 was determined by pre-testing the source pond water for coliforms levels at Water for Cambodia's local water-testing laboratory in Siem Reap. Based on a test of two samples taken from this source on October 1, 2015 and tested at Water for Cambodia, the two samples were found to have turbidities of 112 and 110 NTU, total coliforms of 300 and 162 CFU/ 100 ml, and *E. coli* levels of 68 and 26 CFU/ 100 ml. This water was determined to be sufficiently dirty for the purposes of this study.

Once the source water was determined, and the LBSF was ready for testing, water was collected from the local water source and pumped into a 1500L-holding tank to be delivered to the Trailblazer worksite. This holding tank was used for the daily storage tank fillings during the testing period. Control water samples were collected from the storage tank at the same time of BSF filling during each weekly test period. Experimental water samples were collected from the outflow of the BSF after the water had the opportunity to sit in the BSF for one overnight pause period (residence time).

The water samples were collected by the principal investigator and tested at Resource Development International (RDI) water testing laboratory in Phnom Penh. This laboratory was chosen based on consultation with TF staff and after a laboratory site visit by the principal investigator. This laboratory was chosen because it has the best laboratory equipment and methods available in Cambodia. Sample bottles were obtained from RDI and were flown back to Siem Reap and stored in the refrigerator of the principal investigator. The following sample bottles were obtained:

- 125 mL Sterilized Nalgene bottle for *E. coli* and coliform analysis: 12 each
- 125 mL Acidified bottle for metals (As and Fe) analysis: 12 each
- 500 mL Plastic water bottle for turbidity analysis: 12 each

Using procedures recommended by RDI, two samples were collected on each testing day- one for the experimental (BSF) test and one for the control test. The samples were marked with sample ID, sampling date, and sampling time, and were stored on ice in a small Styrofoam container. For the purposes of coliform testing, the samples were delivered to the RDI laboratory within the recommended 6-hour timeframe (see Table 4.2). The samples were collected at approximately 9:00 am on each testing day, and were delivered to a local airline for a daily 11:40 am flight from Siem Reap to Phnom Penh. A courier from RDI picked up the samples at the Phnom Penh and returned them to the RDI laboratory by 1:00 pm on each testing day. Samples were tested for all of the MIME water quality parameters as listed in Table 4.2.

Table 4.2. Recommendation for sampling, preservation and method of analysis of samples for selected parameters (MIME, 2004).

Parameter	Mode of preservation	Holding time min/max	Minimum Sample (ml)	Method of Analysis
Coliforms	Refrigerate	6 h	100	Membrane filtration
Turbidity	Store in dark; refrigerate	24 h/48 h	n/a	Nephelometer
Arsenic	Refrigerate	28 days	100	Atomic Fluorescence Spectrophotometer
Iron	Refrigerate	6 months	100	Atomic Absorption Spectrophotometer
Total Dissolved Solids	Refrigerate	28 days	100	Gravimetric meter
pH	Analyze immediately	2 hours	n/a	pH meter

While it is generally recommended that pH be tested on site, a portable pH testing kit was not found in Cambodia; therefore pH was tested in the laboratory along with the other parameters. Resource Development reported test results in the form of Resource Laboratory Water Analytical Results reports (see Appendix C), which were e-mailed to the principal investigator. The results of each test were recorded on a Water Quality Test Log instrument (see Appendix D). Tests started on the first day of filter operation, and occurred weekly for six weeks, which theoretically gave the biolayer sufficient time to ripen.

There were some modifications to the pilot BSF as needed to alter water flow or functionality. Any modifications of the original design were noted in direct observation notes and are reported in the Results section.

4.4 Data Analysis

4.4.1 Design and construction analysis

Descriptive notes were taken during the project to qualitatively analyze for themes related to functionality, user-friendliness, maintenance and best practices of using the pilot BSF filter. These notes were collected during the design, construction and testing phases of the project. The parameters included, but were not limited to 1) feasibility of construction/installation, 2) ease of cleaning the biolayer, 3) ease of filling the filter on a daily basis, and 4) other maintenance issues. The identified themes found in the qualitative data were used for content in the BSF User Manual and will produce recommendations for further modifications and further research of large BSF testing and deigns.

4.4.2 Cost analysis

A simple cost analysis was performed using the mathematical functions in cost analysis Excel spreadsheet, which is presented in Chapter 5. This cost will be a tool to help Trailblazer Foundation determine if this is a cost-effective technology, and to see how close the pilot is to their target of constructing a community-scale BSF for less than $800.

4.4.3 Water quality testing

An important outcome to be analyzed in this project was the water quality output of the pilot BSF. With the data gathered as described in the Methods section, a quantitative analysis was performed to compare the experimental water (BSF output) to the control water (pond source) at every point in the testing process. These results were compared to other published findings in the literature on water quality outcomes of biosand filters in field settings.

4.5 Protection of human subjects

Since this project did not involve human subjects, approval was not needed by the university Institutional Review Board (IRB) for the Protection of Human Subjects in Research . This was confirmed by the Committee Chair of this project, who contacted the University of Alaska Anchorage IRB Research Integrity & Compliance (RIC) Officer to confirm exclusion from IRB review (N. Nix, personal communication, November 9, 2015).

Chapter 5 Results

5.1 Large biosand filter design

As noted in the background section, the design of a large biosand filter must reconcile the technical differences between slow sand filters and household biosand filters, using the best available current research. After a further literature review was conducted, a large biosand filter was designed to address all of following technical issues:

1. Filtration rate and flow rate
2. Reservoir volume (constant hydraulic head)
3. Residence time
4. Standing head
5. Media specifications and depths
6. Maintenance of the biolayer

5.1.1 Filtration rate and flow rate

The most important aspect of a biosand filter design is the *filtration rate* (hydraulic loading rate), which is the *flow rate* per square meter of sand surface area (CAWST, 2009). The *flow rate* is the rate that the influent water flows down the BSF column through the filter media and into the outlet pipe, measured in liters per minute. Elliot et al. (2008) demonstrated that intermittently operated biosand filters operate at near plug-flow conditions, and each parcel of water travelling through the sand travels at the same speed.

A flow rate in liters per minute is calculated as follows:

*Flow rate (L/min) = Filtration rate (L/m^2/hour) * Surface area (m^2)/ 60 min*

Different sized household BSFs should always have the same target filtration rate, but will have different target flow rates based on the surface area of the BSF design (CAWST, 2012). It should be noted that in BSFs the target filtration rate is measured when the filter is first installed, which is known as the "clean bed filtration rate." The filtration rate will decrease to zero during the batch (as the water load passes through the filter). Also, the filtration rate will decrease between fillings as BSFs age and the sand slowly becomes clogged (CAWST, 2012).

It is important to maintain sufficiently low flow rates; high flow rates, even for a short time, can result in shear forces that cause pathogens to become dislodged from the media and re-enter the water stream (D. Baker, personal communication, October 8, 2015). These pathogens could include *Cryptosporidium* oocysts, and also organic matter (CAWST, n.d.)

There are a few other important factors that affect flow rate, including the influent water temperature and turbidity, and the length of the sand column and the properties of the sand (particularly size and uniformity). Therefore, increasing the surface area or hydraulic loading, pre-filtering the influent water, using a filter in the tropics as opposed to cold climates, decreasing the sand height or changing the sand type to a coarser sand can all result in a higher flow rate (CAWST, n.d.).

As noted in the background information, for a household biosand filter the *maximum* filtration rate is 0.4 m^3/m^2/hour (or liters/m^2/hour), which decreases towards zero during the batch, giving an average filtration rate of approximately 0.2 m^3/m^2/hour. For slow sand filters the filtration rate has historically been 0.1- 0.2 m^3/m^2/hour. Filtration rates have been calculated so that the filter can provide an amount of water that is adequate for the user, while ensuring that the water is sufficiently cleaned (CAWST, n.d.). Slower filtration rates could possibly produce cleaner water, but at rates that would discourage uptake of the technology.

For the standard Version 10 of the CAWST concrete household filter (2012), the maximum flow rate was calculated to be <u>0.4 liters per minute</u> using the following calculation (*note that the v.10 BSF has a sand surface area of 0.06 m^2*):

Max Flow Rate = Filtration Rate * Surface Area

= 0.4 m^3/m^2/hour * 0.06 m^2

= (400 liters/ m^2 * 0.06 m^2)/60 minutes

= <u>0.4 liters/min</u> (CAWST, 2012)

Since the large BSF in this project operates under continuous flow (maintained by a constant head), the flow rate is calculated using a filtration rate of **0.2 m^3/m^2/hour**. This will provide for low enough flow rates to increase contact time, which is very important for contaminant removal.

Based on the size specifications of the 700-liter tank used in this project, the target flow rate was calculated using the surface area of the tank, which is 0.53^2 (see section 5.2):

Continuous filtration rate = 0.2 m^3/m^2/hour

Continuous Flow Rate = target filtration rate x surface area / 60 min

= (200 <u>liters</u> * 0.53 m^2) / 60 min

= 1.8 L/min

During installation of the pilot 700-liter filter, this was the target flow rate.

5.1.2 Reservoir volume (constant hydraulic head)

One of the biggest factors that affects the microbiological performance of a BSF is the hydraulic load (reservoir volume), which is the volume of water above the standing head. Since the standing head is at the same level of the top of the outlet pipe, and is the minimum amount of water in the tank at all times, the water above that level is the driving head that pushes water through the system (See Figure 5.1). The reservoir volume should be kept low enough so that the filtration rate is never exceeded. Research has confirmed that reducing the hydraulic head is a significant factor in improving bacterial removal in household BSFs (Jenkins et al, 2011; Baumgartner et al., 2007).

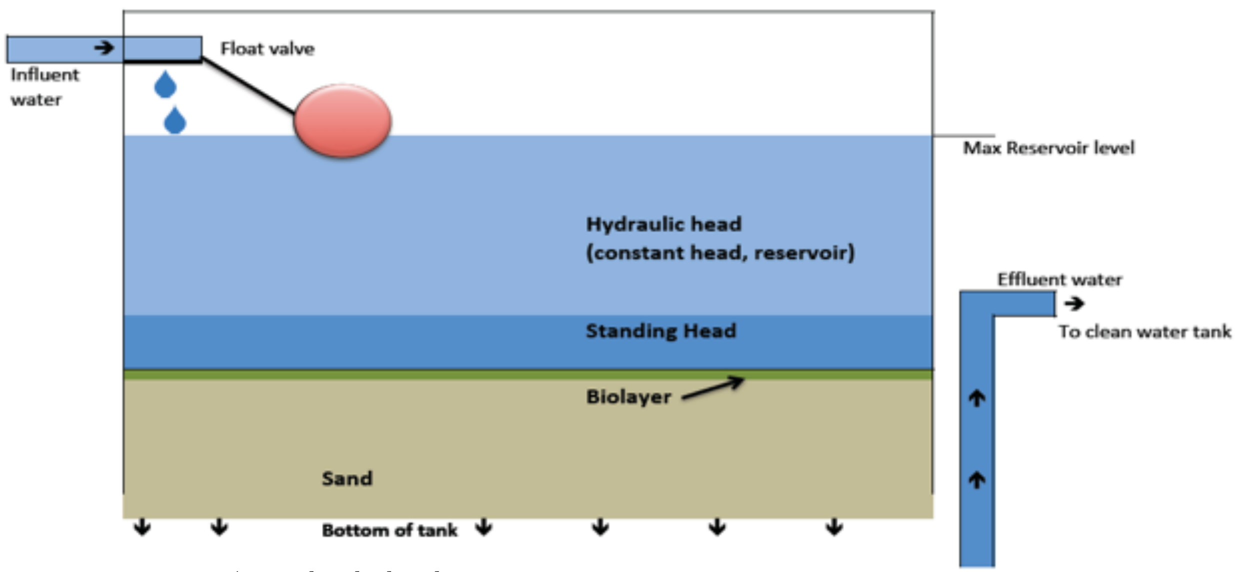


Figure 5.1. Hydraulic head in a LBSF

In this project design, the reservoir volume was regulated by a constant head device to ensure that constant head did not exceed hydraulic loading limits. (Note that the terms constant head, hydraulic head and reservoir volume are used interchangeably in this example).

A CAWST biosand filter advisor to this project suggested that to achieve the target hydraulic loading rate of 0.2 m^3/m^2/hour, the sand bed depth needed to be approximately six times the height of the reservoir, which is about double that of the household BSF (D. Baker, personal communication, October 17, 2015). For this project design, a conservative head size was used to keep it well within this reservoir:bed ratio. This created a low constant head and low filtration rate, while allowing for a sufficient reservoir.

Since the system operates under low flow conditions, it will needs to operate for long periods of time in order to produce sufficient volume of water (R. Cantwell, communication, October 16, 2015). Loading a large BSF one batch at a time would be difficult for the user and would not generate significant quantities of clean water.

A solution to this dilemma was to implement a source storage tank into the design. This tank is larger than the filter tank (1000+ liters), and is elevated so that it gravity feeds the filter tank. An advantage of having this extra tank is that it allows a much larger reservoir so that an entire water tank can be piped to flow through the BSF without intervention (D. Baker, personal communication, October 8, 2015).

In this design, a widely available float valve (i.e. a brass valve commonly used in toilets) regulates the gravity flow and maintains a constant head at a pre-determined level above the sand. The height of the valve is then adjusted during testing to ensure that the flow rate does not exceed the target flow rate of 1.8 L/min. The height of the constant head, and the float valve, is discussed in Section 5.1.5.

5.1.3 Residence time

While a large BSF theoretically operates under constant flow, under realistic conditions in the field it will be fed intermittently as the storage tank may go empty. It is highly likely that a LBSF in a field setting will have frequent pause periods. This is very acceptable, as residence periods will only improve the quality of the effluent water. Residence time increases *contact time* with the sand, which recent research has confirmed to be one of the crucial factors in bio-contaminant removal in the household BSF (Jenkins, Tiwari & Darby, 2011; Elliott, 2011). While pause periods are acceptable, they should not exceed 48 hours, as recommended by CAWST. If the pause period is extended for too long, the beneficial microorganisms will eventually consume all of the nutrients/pathogens and will die off (CAWST, 2009). The training manual produced for this project includes operation instructions for the user to not allow pause periods to exceed 48 hours.

5.1.4 Standing head

During a pause period, the water level will decrease to the standing head level, as hydraulically regulated by the outlet spout. The standing head fulfills a few important functions. First, it allows for oxygen to diffuse into the biolayer. CAWST (2009) states that the standing water depth can be 4-6 cm, but ideally it should be at 5 cm. More than 5 cm could result in lower oxygen diffusion and consequently a thinner biolayer. The standing water also provides a cushion to help diffuse the energy of the influent water pour. And lastly, the standing water protects the biolayer from drying out. It needs to be of sufficient level so that the water does not evaporate if the filter is not used for an extended period. CAWST (n.d.) states that a 5 cm layer could evaporate in 3 to 4 days in a hot climate, which would kill the organisms in the schmutzdecke. Unlike a small concrete BSF, the large plastic BSF tank will have a lid, which will limit evaporation. Therefore, a 5 cm layer should be sufficient in order to keep the schmutzdecke immersed, as long as the LBSF does not go unused for an extended period.

5.1.5 Media specifications and depths

Sand characteristics

The sand can be seen as the "engine" that drives the purification process of the filter. There are two important factors related to sand: the sand bed depth and sand composition. The important considerations for composition are sand size, uniformity and sand type. Sand size is perhaps the most important factor; Jenkins et al (2009; 2011) found that bacteria and virus removal was significantly better for biosand filters with finer sand.

A maximum grain size (d_{max}) for the filtration sand is recommended by CAWST to be less than 0.7 mm to ensure that all sand grains are small enough to contribute surface area to aid in the attachment of pathogens. The effective size of the sand (d_{10}) should be 0.15 to 0.20 mm and the uniformity coefficient (UC) should be less than 2.5 (Ngai & Baker, 2014).

Crushed rock sand is generally considered the best choice, and is recommended by CAWST (n.d.). However, this sand is often not available. Duke and Mazumder (2009) found no significant difference between similarly prepared sand filters using river, beach or crushed quarry rock sand. While crushed rock sand produced the best results initially, all the differing sand filters performed equally after filter maturation. Manz also noted that a single layer of local river sand of variable size is often used as the filtration media instead of the D-BSF's two different size layers of crushed sand (CAWST, n.d.). Bank river sand is a suitable replacement, as long as it has been cleaned of pathogens and organic material. River sand needs to be disinfected with chlorine or by sun drying (CAWST, 2009).

Sieving the sand with a wire mesh or perforated plate sieve (opening size of 0.7 mm) to remove the oversize sand, then washing the sand with water as many times as necessary to remove sufficient amounts of the finer sand, achieves the recommended ranges for the effective size and uniformity coefficient of the filter sand (Ngai & Baker, 2014).

In this project, sand was prepared using river sand that was sieved (to 0.7mm d_{10} maximum) and washed, as suggested by CAWST. This is the same sand that Trailblazer Foundation uses in constructing household biosand filters. While a “perfect” river sand size may not be obtained, this project helped demonstrate if commonly available sand in the area is suitable for large BSF use.

Sand levels

In a household BSF, CAWST (n.d.) recommends a minimum of 50 cm to provide surface area for adsorption of contaminants. Beyond that, it is only limited by the size of the container, the desired filtration rate, and the quantity of water needed. The advantage of a large, community-scale BSF is that a large sand bed can be constructed to process more water, and thereby serve more people. The cost of sand is not a prohibitive factor.

To determine our reservoir and sand volumes (and depths), we first determined how much available space we have in a 700-liter water tank. First we calculated the “working height” that was used inside the tank for all layers: the sand, drainage gravel, reservoir volume and standing head.

“Working height” $= h_{reservoir} + h_{standing} + h_{sand} + h_{gravel}$

There are some pre-determined constants. The standing water level was the standard 5 cm ($h_{standing} = 0.05$ m). We used a conservative 20 cm for the gravel layers (7 cm for separating gravel and 13 cm for drainage gravel), so therefore $h_{gravel} = 0.2$ m. The total available tank height is 1.35 m.

Then we calculated for reservoir+sand column height:

$H_{reservoir+sand} = h_{totalBSF} – h_{gravel} - h_{standing}$

$H_{reservoir+sand} = 1.35 \text{ m} – 0.20 \text{ m} –0.05 \text{ m}$

$= 1.10 \text{ m}$

To give a margin of error at the top of the container, a working height of 1.0 meter was used.

Upon consultation with the CAWST advisor Derek Baker (personal communication, October 8, 2015), it was determined that to achieve a target hydraulic loading rate of 0.2 m^3/m^2/hour, the sand bed depth needed to be approximately six times the height of the reservoir, which is about double that of the household BSF. For this design, an initial sand:reservoir ratio of 5:1 was used, as more sand could be added later if the flow rate was found to be excessive. With this, the sand and reservoir depths were calculated:

$h_{sand} + 5(h_{reservoir}) = 1.0 \text{ m}$

$h = 0.17$

$h_{sand} = 0.73$

To leave room to add more sand or increase reservoir, we started with the following depths:

Sand depth: 75 cm

Reservoir: 15 cm

Separating and drainage gravel layers

In a household BSF, the separating layer separates the filtration sand from the drainage layer so that filtration sand cannot move down and clog the outlet pipe. The drainage layer covers the outlet pipe and allows for proper water flow and collection at the bottom of the BSF. It provides a barrier so that the water travels equally through the filtration bed and does not converge to the outlet pipe (CAWST, 2012).

For media size selection, it is recommended that each successive layer be not more than twice the average grain size of the layer above it (CAWST, 2012). Therefore, the grain sizes were measured as such:

- Sand size: max 0.7 mm
- Separating layer: 0.7 mm – 6 mm
- Drainage layer: 6 mm -12 mm

The recommended depth levels for the separating and underdrain layers is 5 cm each, which allows for variation in the outlet pipe placement and variation in sand levels.

For a large, community size BSF, the functions of the drain layer can be augmented by perforated PVC pipes, which can reduce the amount of gravel (and thereby weight) required. A pipe that covers a larger portion of the bottom of the filter also allows for more drainage points into the outlet tube, versus the single drainage tube of the household BSF. For this design, CAWST was consulted and they recommended a drainage pipe with approximately 10-20 holes that are approximately 6 mm in size (D. Baker, personal communication, October 8, 2015).

For this design, a 60 mm PVC pipe was chosen as the drainage pipe, to be laid at the bottom of the BSF tank across the tank at its diameter. The size of the pipe was chosen in consideration of being strong enough to bear the load of the tank's gravel, sand and water, and allow for sufficient drainage flow. The PVC pipe was drilled with approximately twenty-five 5-mm holes.

Since the drainage gravel layer should cover the top of the PVC pipe, a total drainage gravel layer of 13 cm was used (see Figure 5.2).

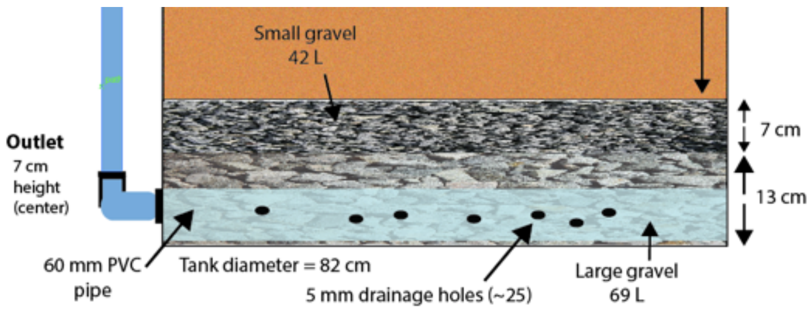


Figure 5.2. Diagram of gravel layers.

The height of the separating layer above the drainage layer was chosen as 7 cm. Both of these are slightly higher than recommended, in order to account for a margin of error in this pilot project. Future recommendations for this design are addressed in Chapter 9.

5.1.6 Maintenance of the biolayer

The biolayer, or "schmutzdecke," is one of the most important mechanism of bio-contaminant removal in both SSFs and BSFs, although it is unclear what the exact mechanisms or scope of the role of the biolayer is in this process. There are many organisms at work in the schmutzdecke, including algae, plankton, diatoms, rotifers and bacteria (Huisman & Wood 1974). It does appear that the schmutzdecke has a modest to significant effect on bacterial removal and little to no role in virus removal. Elliott et al. (2011) found that viral removal was not related to modification of media by microbes, but to the activity of the microbiological community within the filter. Removing the schmutzdecke caused no decrease in viral reductions; however, the bacterial removal did significantly decline. The authors note that virus reduction improved with aged media during pause periods, which is consistent with what has been observed in continuous flow operated SSFs. The Center for Affordable Water and Sanitation Technology state that it may take up to 30 days for the biolayer to fully form. During that time, both the removal efficiency and the oxygen demand will increase as the biolayer grows (CAWST, 2009).

As Young-Rojanschi & Madramootoo (2014) note, the original theory leading to the development of the BSF was that a deep standing head lead to anaerobic conditions within the schmutzdecke. They found that even with a reduced standing head in the control (intermittent filter), anoxic conditions existed in the upper media layers by the end of the residence period. This could suggest that the low standing head formed during intermittent operations may not be as important as originally thought, and further research is needed (Young-Rojanschi and Madramootoo, 2014). In slow sand filter designs, standing water can be maintained at higher levels because the continuous flow of water provides oxygen to the biolayer of the SSF. CAWST (n.d.) suggests that lower flow rates may allow for biofilms to become better developed. Based on this research and recommendations, the design of the large scale BSF accounts for a continuous, low flow and moderate head to allow for development of the schmutzdecke.

Another consideration in a BSF is the protection of the biolayer from disruption as water is added to the unit. In a normal BSF, a diffuser plate is used to disperse the water as it is poured into the filter (CAWST, n.d.). In the LBSF design, a diffuser, or “splash guard,” was placed just below the float valve outlet on the inside of the filter tank.

After continued use, the biolayer will become clogged. The recommended cleaning method for household BSF's is called 'wet harrowing' (See Figure 5.3). This method involves swirling the water on top of the biolayer to dislodge particles, while trying not to disturb the sand layer, and then decanting the resulting cloudy water. The advantage of wet harrowing is that it does not disturb the biologically active slime layer that has formed between sand grains. The technique is effective, requires little work, and disturbs the biological layer less than other methods, such as sand removal, cleaning, and replacement (CAWST, n.d.).

Figure 5.3. Wet harrowing in a household BSF

A 700-liter BSF tank is of a manageable enough size to allow for wet harrowing by hand. The main difference between this technique in a LBSF and a household BSF is that instead of using a cup to decant dirty water, in the LBSF a drainage valve is designed in the side of the tank at the level of the top of the biolayer, to allow for easy drainage of the dirty water. Since this water will contain a high level of biological contaminants, instructions are included in the LBSF Construction and Operation Manual to properly dispose of the dirty biolayer water.

5.2 Construction, modification and testing of the pilot LBSF

For a period of 8 weeks, the pilot BSF system was constructed and tested on the site of TF, using the design recommendations described in previous sections. A 700-liter plastic tank was chosen that already existed on the TF site. A current plastic BSF on the market is the Hydraid model, which is of similar size (0.7m height, 0.4m diameter) to the concrete household model. Industry expert Dr. Mark Sobsey of the University of North Carolina considers them to be the best available technology for the developing world (Triple Quest, 2012). Because of this, no technical issues were anticipated with plastic as the medium of a large-scale filter.

The tank specifications were:

- Type: 700 L non-toxic, heat insulated, impact resistant, food-grade polyethylene (see Figure 5.4)
- Height (at widest points) = 1.35 m
- Height (bottom to opening) = 1.52 m
- Diameter = 0.82 m
- Diameter of opening: 0.34 m
- Cross-sectional surface area = $\pi r^2 = 3.14(0.41)^2 = 0.53\ m^2$

Figure 5.4. 700-liter water tank

5.2.1 Three-tank system set-up

The design for this biosand filter system requires 3 plastic water tanks. A 1000-liter horizontal plastic water tank, which has greater volume than the BSF tank, was chosen to be the dirty water storage source tank. A 500-liter horizontal clean water tank was used for the clean water storage tank (see Figure 5.5)

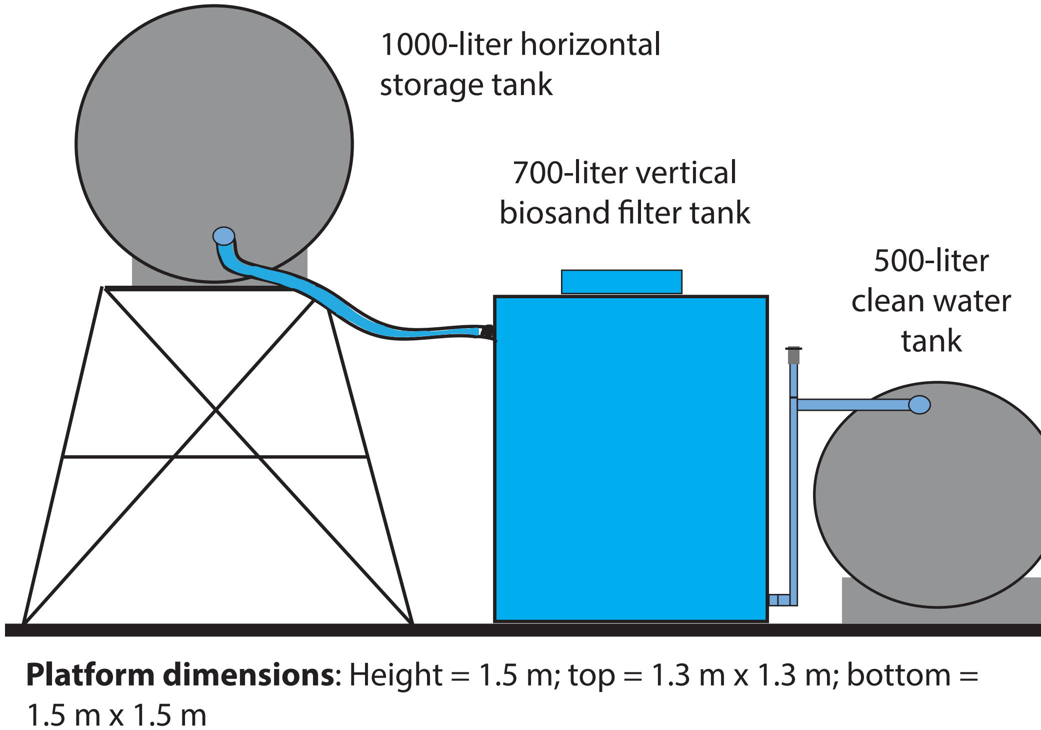


Figure 5.5. Three tank biosand filter system

Since the storage tank gravity feeds the BSF tank, it needs to be elevated to a height greater than the intake valve on the BSF. A platform was designed with the dimensions described in Figure 5.6, and was constructed out of lightweight galvanized steel at a local fabrication shop.

After consultation with Trailblazer Foundation staff, we decided that this design was not only suitable for this pilot project, but is light-weight and portable enough that it could be used for future projects, such as on a floating platform in Peam Ta Ou.

5.2.2 BSF tank preparation

The 700-liter tank was first washed to remove any existing contaminants. An existing 25 mm threaded outlet hole located 7 cm from the bottom of the tank was determined to be suitable as the outlet hole for the effluent water. The initial step was to prepare the drainage tube by drilling twenty-five 5 mm holes cut to 82 cm (diameter of tank), placed at bottom of tank to cover outlet hole and across width of tank and fit snugly against other side of tank (see Figure 5.6).

Next, 81 liters of large gravel was dumped in 3L bag increments into the tank to bring up to a level of 13 cm. Small gravel was dumped in 3.24L bag increments (55-liters) to bring to the total media depth to 20 cm. A shovel was used to even out the layer. A spot check of flow was done to ensure no blockages; a 1.5 L bottle was filled in 7 seconds. Thirty-kilogram bags of sand were dumped into the tank to bring up to a level of 75 cm of sand (95 cm media total), as the design calls for.

Figure 5.6. Drainage pipe at bottom of tank

The outlet pipe was installed from the bottom outlet to a height of approximately 120 cm on the outside of the tank. The outlet pipe was cut down to 5 cm above the sand level so that this would maintain the standing head. Flow tests (filling a 1-liter bottle) were conducted with a 20 cm head, then 17 cm head, then 15 cm head. Results of flow tests:

- 20 cm head = 1 L in 26 sec = 2.3 L/min
- 17 cm head = 1 L in 34 sec = 1.76 L/min

- 15 cm head = 1 L in 44 sec = 1.37 L/min

Since the target flow rate is 1.8 liters per min, the 17 cm head was chosen. Next, the float valve was installed at a height to maintain a 17 cm constant head. The sand level and standing water levels were marked on the outside of the tank. By "eyeballing" where the float valve would reach its shut-off position (see Figure 5.7), a hole was drilled at a 126 cm tank height, which would be the inlet for the float valve. Once tested, the float valve maintained a constant head of 20 cm, which was 3 cm above our target. Flow was confirmed to be too high at 2.4 L/min, and a new valve hole was drilled 3 cm lower. The float valve was re-installed, the constant head was measured to be 17 cm, and flow was measured to be 1.9 L/min. The flow and head stayed steady after several minutes of testing.

Figure 5.7. Estimating position of the float valve.

On November 3, 2015, the tank was deemed to be ready for water quality testing. The storage tank was connected to the BSF tank with polyethylene tubing and PVC fittings, with a shut-off ball valve placed on the outside of the storage tank. The top of the outlet pipe ran across to reach the clean water storage tank. The clean water storage tank had to be raised using bricks to bring its inlet to the same level as the top of the BSF outlet pipe. This is one of the most important aspects of tank configuration, as it allows for proper flow into the clean water tank while maintaining the standing head. See Figure 5.8 for a diagram of the full tank system design. Note that in this pilot system, there was a natural 20 cm drop-off between the BSF tank and the clean water tank.

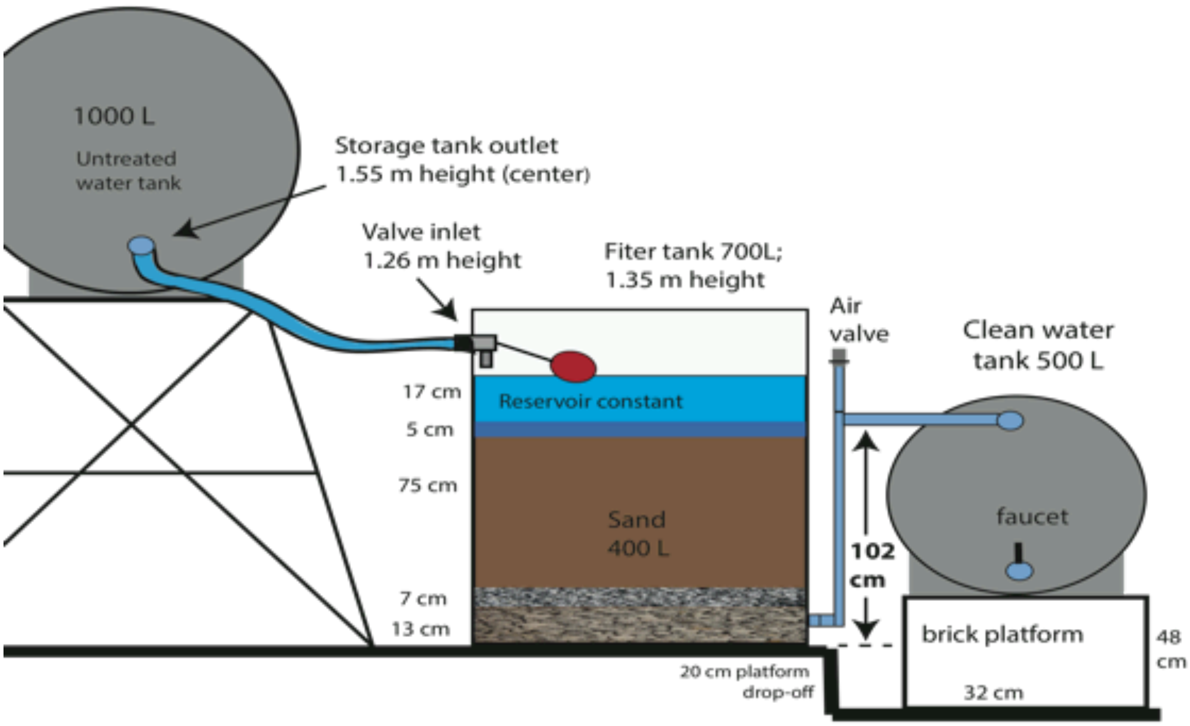


Figure 5.8. Final tank configuration

For the next 6 weeks, the storage tank was filled with water from a nearby pond as described in the Methods section. The flow was checked on a regular basis, and water testing was done on a weekly basis.

Overall, it was fairly straightforward to construct the system based on the design. The primary TF staff involved with the construction was the TF Biosand Filter Team Leader, who had no previous experience with this type of design. But due to his basic understanding of the biosand filtration process, the needs and barriers of users in Cambodia, and his understanding of the sourcing of materials in the region, his input was invaluable. There was a considerable amount of problem solving regarding the types and sizes of PVC fittings to use in the design. All of the final components chosen have been included in the Large Biosand Filter Construction Manual (see Appendix E).

During the course of this project, the principal investigator discovered that Samaritan's Purse was concurrently implementing these types of community-scale biosand filter systems. The WASH manager for Samaritan's Purse, Dr. Ray Cantwell, organized a site visit for the principal investigator and two TF staff, including the BSF Team Leader, to visit a community-scale BSF installation at a school in the village of Svay Chek, near Siem Reap. During this visit, several observations were made that contributed to the design and construction of this BSF pilot project (see Appendix F). This included the following design components:

1. Octagon PVC drainage pipe at the base of the filtration tank
2. One layer of small gravel (0.7- 6 mm) only used for drainage layer
3. Use of a hollow steel pole to plunge sand after water is added in order to free trapped bubbles and ensure sand saturation
4. Increase constant head and initial flow by 25 to 30% over target flow rate to compensate for loss of flow during maturation of filter
5. Optimal type of float valve and splash guard
6. Biolayer cleaning drainage ball valve

Observations 5 and 6 were used in the modification of our filter; observations 1-4 were included in the installation instructions in the Large BSF Construction Manual.

5.2.3 Observations and modifications

A few issues were encountered with the system, which were adjusted during the testing period. On November 7 it was discovered that the float valve outlet had been twisted by about 30 degrees, which could have affected the max head. The valve was adjusted and tightened.

On November 10, it was noticed that the standing head was too low in spots due to the top sand land layer being uneven, so the outlet pipe was raised by 2 cm to increase head. By November 13 the flow had decreased to 1.0 L/min, far below our target flow rate. We realized that this was due to raising the standing head 3 days earlier, which decreased the hydraulic load. To increase the flow, we raised the float valve inlet by 2 cm and increased the constant head back to 17 cm (see Figure 5.9). This had a modest improvement on flow; the flow was tested to be 1.2 L/min five days later.

Figure 5.9. New valve inlet w/ old holes covered by duct tape

On November 14, Dr. Ray Cantwell and four other staff from Samaritan's Purse did a site visit of the Trailblazer Foundation to inspect our LBSF project. As the only other organization in Cambodia constructing community-scale SSF (and perhaps one of the few in the world), they gave valuable feedback. They suggested to use all solid PVC rather than flexible polyethylene tubing if possible, to put screens in our airflow valves, and to raise the air flow valve above the clean water tank height (to prevent back flow into the valve). The recommendations on the air valves were implemented immediately. In a follow up conversation with Ray Cantwell on November 20, he suggested that another method to make small increases in constant head (if needed) would be to bend the float valve arm.

Dirty water was filtered through the BSF tank until December 10, 2015. On this day, the biolayer was cleaned with the wet harrowing technique. To ease the process for the cleaner, a harrowing tool was used. This tool was a small "squeegee" attached to a stick of PVC pipe. After harrowing, the dirty water was emptied into a bucket using a cleaning ball valve that had been installed at the height of the biolayer earlier that day (see Figure 5.10).

Figure 5.10. Wet harrowing using the squeegee tool while draining the dirty biolayer water

An important aspect of HWTS systems is the presence and maintenance of clean storage and transport containers. The design of the system includes an outlet hose coming from the clean storage tank. It includes a flexible hose to readily fill standard 20-liter water jerry cans. The implementing organization (Trailblazer Foundation) makes it standard procedure to educate recipients of BSFs on hygienic techniques of water storage and transport.

During the whole testing period, water was added to the BSF tank on 29 days, and there were 8 pause days in which no water was added. In total, 23,000 liters of water were filtered. On filtration days, an average of 793 liters per day was cleaned. The final design can be seen in Figure 5.11.

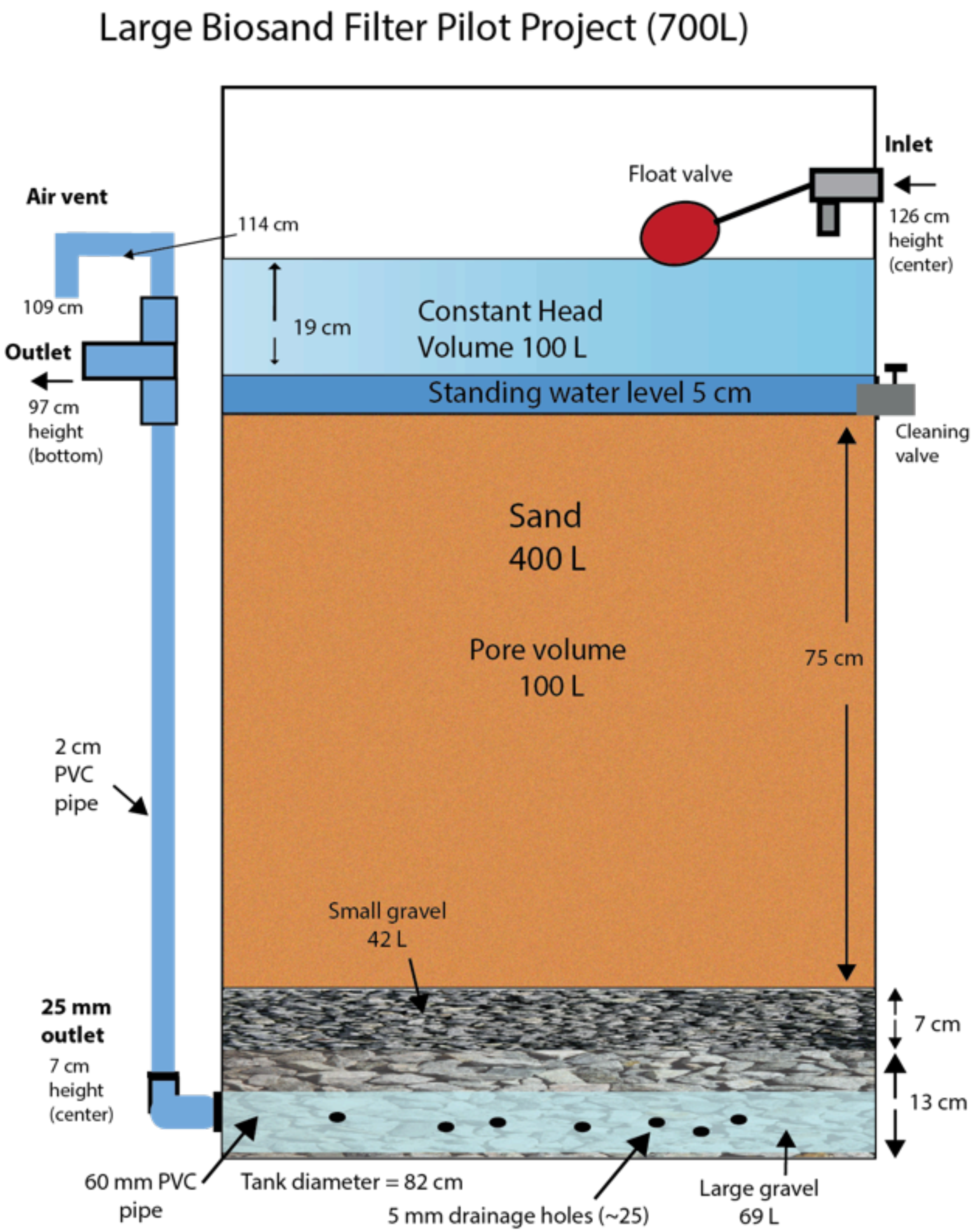


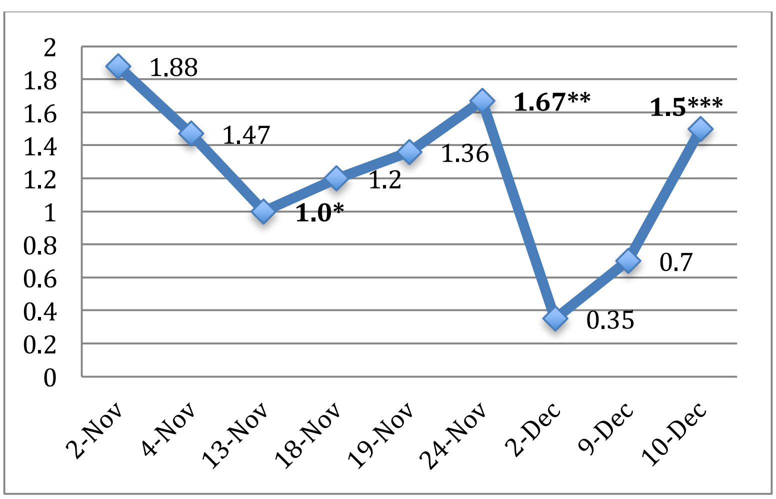
Figure 5.11. Final design of experimental LBSF

During the construction, testing and implementation phases of the project, descriptive notes of field observations (see Appendix B) were recorded by the principal investigator and were later qualitatively analyzed. These descriptive notes included design modifications, anticipated needs and issues users might have during implementation, and recommendations for future designs. Many of these have been noted in the previous sections, and the descriptive notes formed the basis of the Large Biosand Filter Construction Manual (Appendix E).

5.2.4 Water test results

BSF effluent water flow rate

Water flow testing was conducted on a regular basis to determine how quickly the BSF clogged and the flow rate decreased. From our initial flow of 1.88 L/min (slightly above the target rate of 1.8), the flow decreased to a low of 0.35 L/min at week 6 (see Figure 5.12). On this day the biolayer was cleaned using the wet harrowing method. After refilling the BSF tank, the flow was re-measured and found to be 1.5 L/min.



* constant head was decreased from 17 to 15 cm
** head was manually increased to maximum
*** first flow test after cleaning of biolayer

Figure 5.12. Chart of effluent water flow

Water quality testing

Water quality was tested as described in the Methods section, and the laboratory at Resource Development International reported the results. Of the six water quality priority parameters for small water supplies as defined by MIME (2004), only total dissolved solids (TDS) was unavailable as a testing parameter by the laboratory. Another parameter, arsenic was undetected in all samples at laboratory minimum detection level of 1.6 ppb (CDWQS limit is 50 ppb). All test results are listed in the Water Testing Log in Appendix D.

Of three common water quality indicators, *E. coli*, total coliforms and turbidity, the BSF had the following results. Turbidity decreased during the maturation of the filter to a peak reduction of 86.3% on the fifth week (see Figure 5.13).

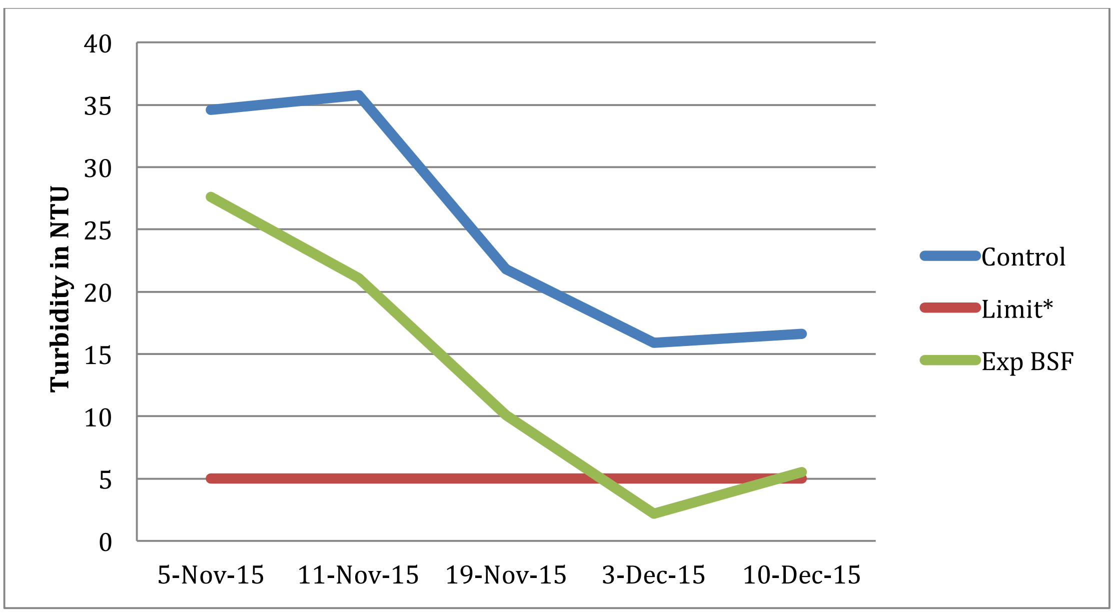


Figure 5.13. Turbidity: Experimental BSF versus Control

E. coli levels (colonies/ml) decreased by 97.1% on week five (see Figure 5.14).

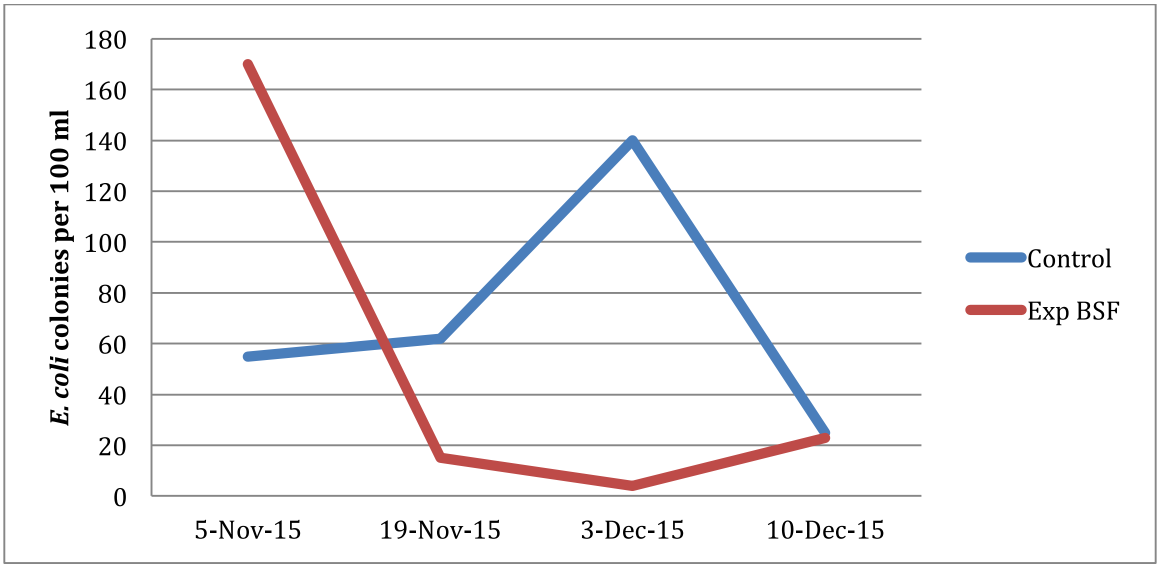


Figure 5.14. E. coli Experimental BSF versus Control

Similarly, total coliforms decreased by 81.7% on week five (see Figure 5.15)

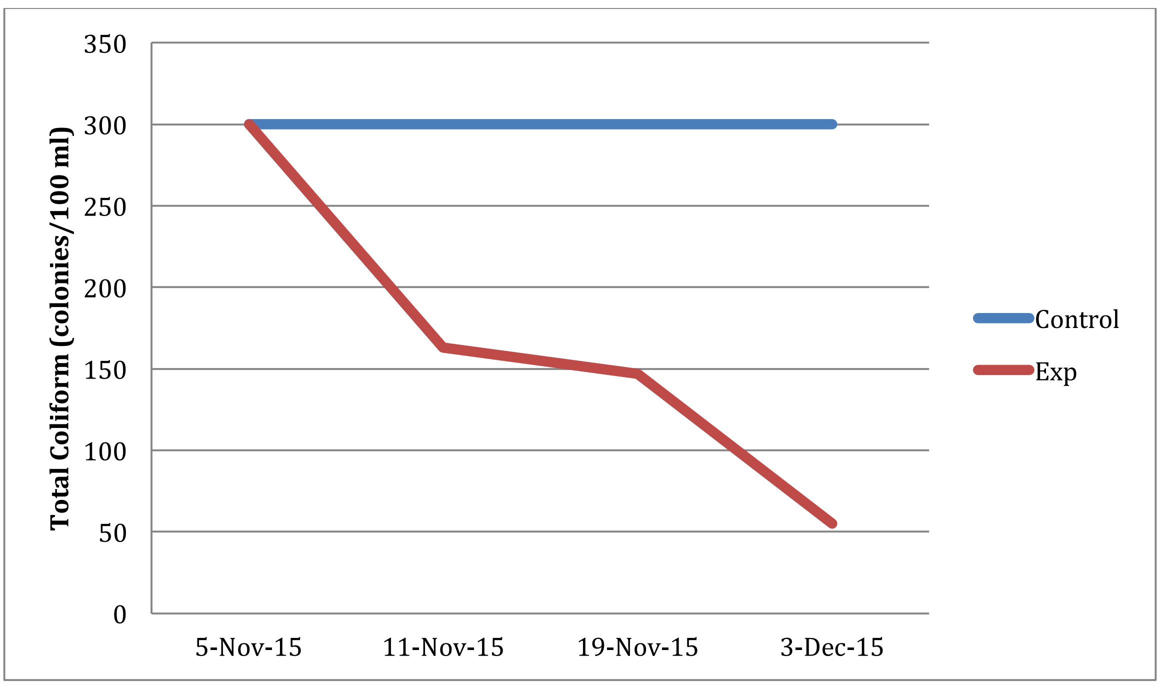


Figure 5.15. Total Coliform Experimental BSF versus Control

While these results are encouraging, it is difficult to fully interpret the results. For example, in both the control and BSF samples, total coliforms were often "too numerous to count" (TNTC) by the laboratory, which is defined as more than 300 colonies per milliliter. The reductions noted in Figure 5.13 use 300 colonies/ml in place of TNTC as a conservative estimate. On week two, there were no *E. coli* colonies present in either the control or the sample. In week one, the total coliforms were three times higher in the BSF samples than the control samples; although this might not be surprising considering that the BSF had just started operating. Other limitations of the water test results are discussed in Chapter 7.

5.2.5 Cost analysis

The target cost of a community-scale bio sand filtration system as defined by Trailblazer Foundation was $800. The cost of this design comes in at $930 (see Table 5.1). In comparison, the cost of the Samaritan's Purse community-scale biosand filtration system is approximately $2000 (see Appendix F), although their system includes a large concrete platform with PCV plumbing, faucets and sinks. Since the design for Trailblazer is intended for a floating platform, it is more portable and cheaper.

Table 5.1 Cost Analysis Worksheet

Estimated parts cost for a 3-tank LBSF system in Siem Reap Province			
Item	Unit cost	Qty	Total
1500 L tank (w/ lid & caps)	225	2	450
700 L tank (w/ lid & caps)	125	1	125
Storage tank stand	135	1	135
PVC pipes, fittings, connectors			50
Small tools, tape, glue, misc.			20
Crushed rock- 25kg bags	10	15	150
TOTAL			$930.00

As a cost-benefit analysis, consider that a 700-liter BSF system, which produces 1.8 L/min, filters for 12 hours per day, would produce approximately 1300 liters of filtered water. Considering that a household BSF produces about 60 liters per day, it would take 22 household BSFs to produce the same quantity of water. Since household BSFs only cost $20 each, that would be a total cost of $432.

5.2.6 Developing community partnerships

One unexpected outcome of this project was a development of collaboration between non-governmental organizations working within Cambodia on biosand filtration. As described earlier, the Centre for Affordable Water and Sanitation Technology put the principal investigator in contact with Dr. Ray Cantwell, the Water, Sanitation and Hygiene Manager for Samaritan's Purse. Not only was Dr. Cantwell an invaluable resource for the Large BSF design, the project facilitated a dialogue between Trailblazer Foundation and Samaritan's Purse (SP), who were largely unaware of each other's activities regarding BSF installation in Cambodia. Dr. Cantwell and four Samaritan's Purse staff, who were in Siem Reap for a conference, visited Trailblazer Foundation to observe and provide input our community-scale BSF pilot. In addition, the SP staff toured the household BSF construction operation of Trailblazer and observed different construction techniques and methods. Two days later, three other SP staff did a site visit. In both visitations there was a sharing of knowledge regarding BSF construction and implementation. The program director of Trailblazer and the WASH manager of Samaritan's Purse met and discussed possibly collaborating in the future on community-scale biosand filtration, or other BSF projects. In a specific example, Samaritan's Purse decided they will switch from version 9 of the household BSF to version 10 in 2016. Since Trailblazer has been using v.10, in early 2016

SP staff will again visit Trailblazer to learn more about v.10 construction and implementation.

While Samaritan's Purse does not normally do BSF installations in Siem Reap Province, another organization called Water for Cambodia does do BSF installations. They also use slightly different methods, and the principal investigator visited their compound and director of operations in Siem Reap. There is a lot of discussion in the biosand filtration field about the optimal type of sand to use in BSFs. Water for Cambodia uses crushed rock instead of river sand for filtration. Since this is generally regarded as better sand, and is the same type that Samaritan's Purse uses for their community-BSF projects, Trailblazer will source this sand for any future implementations of a community-scale BSF project, even it is a little more expensive.

5.2.7. Assisting in further research

In the poster presented by Samaritan's Purse to the University of North Carolina Water and Health Conference in 2015 (Cantwell, 2015), one conclusion reached in that study was that mean calcium levels ($CaCO_3$) increased from 42 mg/L in the raw water to 71 mg/L in the filter water, and this warranted "further investigation around calcium leaching from the sand medium." During discussions with Dr. Cantwell on sand sources, he expressed how Cambodia lacked the facilities to properly analyze sand characteristics, and he asked if the University of Alaska would potentially have the ability to analyze sand samples. In fact, there have been no published studies regarding the detailed composition of sand used in BSFs, and how it affects the chemical characteristics of the filtered water (R. Cantwell, personal communication, November 19, 2015).

The principal investigator contacted Dr. Kenneth Severin, the director of the Advanced Instrumentation Laboratory at the Department of Geosciences at the University of Alaska Fairbanks (UAF). As a potential undergraduate project, Dr. Severin has agreed to analyze sand samples from Samaritan's Purse to answer the following questions:

1. Characterize the composition of the sand (based on the tools/time/costs),
2. Develop some tools or guidance that can be used by laymen in sand selection.

Answering question 2 could be valuable because in Cambodia, for example, there are five different crushed rock sand sources, and it is unclear which is the best to use (R. Cantwell, personal communication, November 21, 2015).

Dr. Severin received crushed rock samples from Dr. Cantwell on January 11, 2016, and has agreed to perform the following analysis:

1. Bulk elemental analysis by X-ray fluorescence
2. Estimation of proportion of grains by each mineral type

This was another unplanned outcome of this Practicum Project, and hopefully it will be valuable towards furthering the field of research in biosand filtration. As Dr. Cantwell (personal communication, November 21, 2015) notes:

> "There have been about 500,000 BSFs installed to date around the world. If we collected sand samples from the largest 8-10 implementers, we could characterize the sand in more than 70% of these filters. That would be useful information for implementers and future researchers."

Chapter 6 Discussion

The lack of clean water is an urgent crisis in Cambodia, as it is in much of the developing world. While there have been many technological advances in recent years in the field of clean water technology, many require particular expertise, have high costs to implement and/or maintain, and are impractical to implement in remote field settings. Biosand filtration is an appealing solution due to its low cost, ease of use to the consumer, and abundance of raw materials needed for their construction. Household BSFs are an ideal model of a low-cost, basic design; it consists of concrete, sand, gravel, a piece of copper tubing and a plastic diffuser plate.

While a community-scale BSF is more complex, all of its components are also available in developing world settings. Plastic water tanks and PVC fittings can be found anywhere in the world. This project has demonstrated that a large BSF, once it is properly designed, can be feasibly and economically constructed. While a series of 22 BSFs could feasibly produce the same amount of water at about half the initial cost of a community-scale system, a series of BSFs would require a considerable amount of labor and upkeep to fill, maintain and regularly clean. Household BSFs are also bulky and heavy. At a weight of 80 kg each (CAWST, 2012), 22 BSFs would weight 1.76 metric tons before the addition of sand. An empty LBSF tank system weighs a fraction of that, making it a more feasible option for remote settings, including on a floating platform on Tonle Sap Lake.

A community-scale BSF filter will require considerable buy-in and commitment from the community. One disadvantage of a system like this is that it requires large volumes of water to be loaded to a height of more than two meters. In practice, this will require a gas powered pump (a foot pump is a possible, yet less practical, alternative). A gas pump will require fuel purchases to operate, and someone to operate the pump on a daily basis. In addition, someone will need to be responsible for checking the LBSF for general maintenance, including leaks, clogging, flow rates, and the cleaning of the biolayer.

The community of Peam Ta Ou has already laid down the groundwork for making a community-scale BSF project sustainable. The principal investigator, along with the TF Field Director, met with representatives from the Analytic Development Issue Center, who are offering support to this project. They disclosed that the organizations World Fish, Hurredo, Trailblazer Foundation and the local community council have combined to raise $6500 for this floating water station. As previously noted, the 3 meter by 5 meter platform has already been built. The community plans on establishing a Water Committee to operate and maintain the floating water station. There are 287 families in this community who have raised a total of 170,000 Cambodian riel ($42.50) to start a water fund. Families will be expected to contribute 500 riel ($0.13) per drum to go into the Water Committee fund. This will help to ensure the sustainability of a community-scale BSF project.

This pilot demonstrated that maintenance of the BSF is straightforward; it requires only basic monitoring to ensure there are no stoppages or leaks. This project showed that cleaning the biolayer using the same methods employed in household BSF schmutzdecke cleaning is simple and practical. The LBSF also demonstrated that flow was properly restored after schmutzdecke cleaning.

This project has also further demonstrated the ability of a community-scale biosand filter to efficiently clean water. The mechanisms of water purification are the same as the household BSF, and there is no reason to conclude that a large BSF would be a less-effective filter. The water quality testing results in this project support that hypothesis, with the following reductions being found on week five of filter operation:

- *E. coli* (colonies/ml) decreased by 97.1%
- Total coliforms decreased by 81.7%
- Turbidity decreased by 86.3%

The turbidity reduction was similar to what Cantwell (2015) reported on a community-scale BSF of similar design. Jenkins et al (2011) found an 89% turbidity reduction in a ten-week test of 18 experimental filters that were fed river water augmented with wastewater (influent turbidity of 5.4 - 58.6 NTU). It should be noted that the influent water turbidity increased in quality during our test period; this was possibly due to the rainy season subsiding, and therefore the source pond received less run-off.

The *E. coli* results show a greater reduction than the 90% reduction you might expect to find in a household BSF (Ngai et al, 2014). It is not surprising that these results were found at week five, considering that it can take 30 days for the schmutzdecke to fully ripen in BSFs (CAWST, 2012). However, the results showed a decrease in filter performance in week six for unknown reasons. There are many limitations in interpreting the results of these water tests, which are discussed more thoroughly in Chapter 7.

The project partner identified the main goals of this project: demonstrate that a 700-liter BSF can be cost-effectively constructed, using a relatively lightweight design, and with locally sourced parts. The partner participated in the process and has seen the results, and they are moving forward in securing funding to implement this design in the floating village of Peam Ta Ou. They will receive the Large BSF Construction Manual (Appendix E) produced during this project to help guide them in future installations.

What will be key to the scaling up of community-scale BSFs, and all biosand filtration projects in general, is increased collaboration and cooperation between NGOs operating in Cambodia and around the world. This project further demonstrated the value of promoting those partnerships. It is often common for NGOs to operate in isolation from each other, and they often compete for a limited amount of resources; however, funders increasingly want to see collaboration between aid organizations. It is more cost-effective, encourages knowledge sharing, and avoids duplication of services. Samaritan's Purse has been asked to be a technical advisor in future LBSF installations by Trailblazer Foundation. Encouragingly, the two organizations have already taken steps to share knowledge and provide cross training in implementing household BSFs.

Chapter 7 Strengths and Limitations

Water quality results should be interpreted with caution considering several of the following limitations. Of course, this is a small sample size (n=1 at each point in time), with little statistical power. Although proper sample collection procedures were followed, there can be no guarantee of no cross contamination or variances in the samples collected. Some of the samples were collected after different residence times, although the residence time was usually overnight until 9:00 am. Control samples were taken from the storage tank after the water had been sitting in the tank for a varying amount of time (12 to 48 hours). It is unclear what effect that would have on microbiological or turbidity quality of the water.

In addition, residence periods during filter maturation could not always be controlled because of limited access by the principal investigator on weekends and holidays, when TF was closed. It is unknown how extended pause periods, which sometimes exceeded 48 hours (but never more than 60 hours), affected the filter maturation.

Collected samples were put on ice and flown to the RDI laboratory in Phnom Penh, where they arrived five to six hours later. It is unknown how the laboratory stored the samples, or if the transport affected the samples. And finally, the influent water had a high level of turbidity (15.9 – 35.8 NTU). This was due to the fact that we were limited to one consistent water source near the Trailblazer Foundation site, which was a turbid roadside pond. To give a comparison, in a field study of 107 households in Haiti, Baker et al. (2006) found an average influent turbidity of 6.2, which decreased to 0.9 after household BSF filtration. Turbidity in this study was significantly higher, and probably greater than what most users would encounter.

This large BSF is designed with a 700-liter filter tank. This tank was already sitting unused at the TF worksite, meaning it was immediately available and free. However, 700-liter tanks are less common than the widely available 500, 1000 and 1500 liter tanks in local Siem Reap shops. These sizes of tanks are what Samaritan's Purse uses in their community-scale BSF design. Near the end of the project, it was difficult to source 700-liter tanks, although a supplier was eventually found. For the future, it may be easier to design a system using a 1000-liter filter tank, although that would mean a re-design of the system.

The strengths of this project included the fact that Trailblazer staff was closely involved in the construction and testing of the large BSF. This resulted in training that will benefit future installations. The collaboration with Samaritan's Purse was another strength, for the knowledge sharing and exchange of ideas. Likewise, the close collaboration between Dr. Cantwell, CAWST technical advisor Derek Baker, and the principal investigator gives confidence that the final product is a solid design. In fact, the preliminary design in this project was shown to be very similar to Samaritan's Purse community-scale BSF design after the designs were initially shared. This was encouraging to the principal investigator that the scientific principles and calculations behind the original design were sound. All subsequent collaboration and knowledge sharing was beneficial to all involved partners.

Chapter 8 Public Health Implications

A 700-liter BSF that can produce 108 liters per hour, and a maximum of 2,500 liters per day, will potentially increase the amount of low-cost potable water to needy communities in Cambodia, which will have a positive health impact by helping reduce the rates of water-borne illnesses. For example, in Peam Ta Ou, the primary source of drinking water is the Tonle Sap Lake. The residents of these floating villages also have the option of purchasing water for approximately $1.25 per 20-liter container. The cost of LBSF water, as administered by a community water council, will reduce that price ten-fold to $0.13 per 20-liter container. This new technology fulfills one of the Ten Essential Functions of Public Health by advancing new insights and innovative solutions to health problems.

There could be applications for this modified technology beyond Cambodia or similar developing countries. For example, a community-scale BSF might be suitable for circumpolar regions like rural Alaska where there are often substandard WASH resources. Issues of biolayer development, sand acquisition and temperature maintenance would need to be researched and addressed, however there could be opportunities for this type of filtration technology to meet the clean water needs of small communities.

Another function of public health that this project promotes is mobilizing public health partnerships. The strengthening of partnerships between organizations providing clean water solutions in Cambodia will improve the quality of those services, which will have a long-term and sustainable impact on the health of the population.

Chapter 9 Recommendations for Future Design and Research

During the course of this project, there were several discoveries and observations about how to better implement future large BSF systems. These discoveries came about from technical consultation with CAWST, Samaritan's Purse, the input of Trailblazer staff, and direct observation of this pilot project. These include the recommendations below, which are also incorporated into the LBSF Construction Manual:

- use an octagon drainage pipe, with holes drilled on the underside of the pipe to prevent fine sand from entering the pipe;
- increase constant head to increase initial flow rate 25-30% above target rate to account for flow loss during maturation of filter;
- use only one layer of small gravel (0.7- 6 mm) for drainage layer;
- use storage tank and clean water tanks of equal sizes (1500L);
- implement other design alterations including use of outlet hose on clean water tank to allow for ease of filling to the user.

Community-scale biosand filtration is an evolution of the centuries-old practice of slow sand filtration and the decades-old practice of household biosand filtration. There is a need for future research of these systems. Further testing should include the efficacy of LBSFs on virus removal, and how the microbiological removing ability of these filters respond to schmutzdecke cleaning. The issues of user uptake and sustainability need to be explored as well. It could also be very enlightening to understand the health impact to the end user and epidemiological studies that look at the incidences of diarrhea or water-washed diseases before and after implementation of the biosand filter could further shed light on the real-world ability of biosand filters to reduce water-borne and water-washed illnesses.

Hopefully other organizations will find the value of community-scale filters and as they are implemented across the world, new methods and designs will improve the overall functionality of this innovative, yet simple technology.

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Appendices

Appendix A: Community Partner Letter of Support

Trailblazer Foundation
Chong Kaosou village
Slakram Commune
Siem Reap, Cambodia
www.thetrailblazerfoundation.org

12 September 2015

Master of Public Health Program
University of Alaska Anchorage
3211 Providence Drive
Anchorage, Alaska 99508

To Whom it May Concern,

This is a letter of support for Jason Hahn, who will be doing a Master's level project practicum at the site of our organization, Trailblazer Foundation, located in Siem Reap, Cambodia. We support Mr. Hahn in his work to design and test a pilot large-scale biosand filter. We are happy to share with Jason our 10 years of experience of building and implementing biosand filters to villages in Cambodia.

Mr. Hahn will have access to and permission to use relevant data we have collected on biosand filters. He will have access to the project site where his practicum will be conducted. Also, he will have the support of our staff, including myself and Mr. Reth Bony of the Biosand Filter Project Team.

We look forward to the work of Mr. Hahn, as the results of his project will help us determine the design and feasibility of a large-scale biosand filter. It successful, we will move forward in implementing the BSF filter to needy communities in Siem Reap.

Sincerely,

Mr. SorRatanak, MBA
Managing Director
Trailblazer Foundation

Appendix B: Descriptive Notes: Consultation and Field Observations

Descriptive Notes:
Consultation
Large Biosand Filter Pilot Project

EXAMPLE:

Descriptive Note ID# _12______

Date ___10/17/2015

Name of researcher ____Jason Hahn___

Consultant information

Name __Derek Baker_____

Organization ___Centre for Affordable Water and Sanitation Technology (CAWST)_

Title ____Technical Advisor__

Others involved: ___ Lena Bunzenmeyer, International Technical Advisor, CAWST
Ray Cantwell, Samaritan's Purse
Ratanak Sor, Trailblazer

Method of communication __e-mail

Location __Trailblazer Foundation

Technical Issues discussed __Standing water level, tank height, reservoir height/volume

Notes:

Standing water: There is no standing water (supernatant) layer shown in your design. We recommend 5 cm of standing water, which will be at the level of the outlet pipe.
Height of tanks and plumbing: put a valve on the pipe between the storage tank and filter tank for pause purposes.
Reservoir height and volume: This design, like the slow sand filter (SSF), depends on a much lower hydraulic loading rate (max. 0.2 vs. 0.4 m3/m2/hour for SSF vs. BSF) to achieve high removal of contaminants. In contrast, the biosand filter relies on the water residing in the pore space of the sand during the pause period to achieve much of its removal effectiveness. In this design then, the volumes are not as important as the relative heights of the reservoir and sand bed. To achieve the target hydraulic loading rate of 0.2 m3/m2/hour, the sand bed depth will need to be approx. 6 times the height of the reservoir (measured from the top of the standing water to the max height of the reservoir during a run). I mention 6 times because this is approximately double that of the BSF (54 cm / 17 cm = 3.1). This assumes that you will be using the same specs for the sand as CAWST recommends for the BSF.

Descriptive Notes:
Field Observations
Large Biosand Filter Pilot Project

Descriptive Note ID# __________

Date ____________

Location _____________________________

Notes

Appendix C: Instrument: Sample Water Testing Quality Report Form.

RDi CAMBODIA

Resource Laboratory Water Analytical Results

RESOURCE LABORATORY

Client: Trailblazer Foundation		**Water Source:**	NA
Date Received:	5-Nov-15	**Province:**	Siem Reap
Collection Date:	5-Nov-15	**District:**	NA
# of samples:	2	**Commune:**	NA
Preservation:	ice, acid	**Village:**	NA

★★
Sample ID: **TB BSF**

Parameter	Results	Units	Method	Date Analyzed	DL	CDWQS
Manganese	0.05	mg/L	AAS	6-Nov-2015	0.05	0.10
Arsenic	<DL	ppb	AFS	16-Nov-2015	1.6	50
Iron	1.13	mg/L	Colorimetric	6-Nov-2015	-	0.30
Fluoride	<DL	mg/L	IC	10-Nov-2015	0.35	1.5
Nitrate	<DL	mg/L	IC	10-Nov-2015	0.13	50
Nitrite	<DL	mg/L	IC	10-Nov-2015	0.15	3
Chloride	2.50	mg/L	IC	10-Nov-2015	0.18	250
Sulfate	1.59	mg/L	IC	10-Nov-2015	0.11	250
Phosphate	<DL	mg/L	IC	10-Nov-2015	0.62	-
Turbidity	27.6	NTU	Meter	5-Nov-2015	-	5
pH	9.1	pH units	Meter	5-Nov-2015	-	6.5 - 8.5
Conductivity	50	µS/cm	Meter	5-Nov-2015	-	1500
Total Hardness	36	mg/L CaCO3	Titration	5-Nov-2015	-	300
E. Coli	170	cfu/100 mL	MF	5-Nov-2015	-	0
Total Coliforms	TNTC	cfu/100 mL	MF	5-Nov-2015	-	0

CDWQS = Cambodian Drinking Water Quality Standards (2004)

[yellow] Exceeds Cambodian Drinking Water Quality Standard

DL = Detection Limit

TNTC : Too Numerous To Count

Note: TNTC > 300 Colonies

16-Nov-2015

Resource Laboratory

Ann Hall
Health Development Manager

Address: #50A, Royal Brick Road, Preak Thum Village, Sangkat Kbal Koh, Khan Chbar Ampov, Phnom Penh, Cambodia
Lab Phone: 017 794 393, Office Phone: 017 778 533, Lab Email: lab@rdic.org, Website: www.rdic.org

Appendix D. Water Testing Log

Table 1. Total schedule of LBSF fillings, flow tests and water tests at the Trailblazer worksite by Jason Hahn

WK	Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Sat
1	11/1/15	11/2/15	11/3/15 Water 1000L Time 11am Flow	11/4/15 Water 1000L Time 8:30am Flow 1.47 15 cm head	11/5/15 Water 1000L Time 8am Flow TEST #1	11/6/15 Water 0 Time Flow	11/7/15 Water 1000L Time 11am Flow
2	11/8/15 Water 0 Time Flow	11/9/15 Water 500L Time 9am Flow	11/10/15 Water 1000L Time Flow	11/11/15 Water 400L Time 8am Flow TEST 2	11/12/15 Water 0 Time Flow	11/13/15 Water 1000L Time 9am Flow* 1.0 *15 cm head	11/14/15 Water 500L Time 11am Flow
3	11/15/15 Water 1000L Time 2pm Flow	11/16/15 Water 400L Time 9am Flow	11/17/15 Water 800L Time 3pm Flow	11/18/15 Water 700L Time Flow 1.2 19 cm head	11/19/15 Water 1000L Time Flow 1.36 TEST #3	11/20/15 Water 1500 Time 9am/1 Flow	11/21/15 Water 0 Time Flow
4	11/22/15 Water 0 Time Flow	11/23/15 Water 1000L Time 9am Flow	11/24/15 Water 1000L Time 8am Flow	11/25/15 Water 1000L Time Flow	11/26/15 Water 1000L Time Flow 1.67* 20 cm constant head	11/27/15 Water 500L Time Flow	11/28/15 Water 0 Time Flow
5	11/29/15 Water 0 Time Flow	11/30/15 Water 1000L Time 830am Flow	12/1/15 Water 1000L Time 830am Flow	12/2/15 Water 300L Time Flow 0.35	12/3/15 Water 500L Time 9am Flow TEST #4	12/4/15 Water 0 Time Flow	12/5/15 Water 500L Time 9am Flow

6	12/6/15	12/7/15	12/8/15	12/9/15	12/10/15	12/11/15	
	Water 1000L	Water 500L	Water 500L	Water 500L	Water		
	Time 9am	Time	Time	Time	Time		
	Flow	Flow	Flow	Flow 0.7	Flow 1.5		
					TEST #5		

Table 2. BSF Filter flow results

Test #	Test Date	Constant head flow (L/min)	Notes
1	10/30	2.4	20 cm constant head- testing only
2	11/2	1.88	17 cm constant head
3	11/4	1.47	17 cm constant head
4	11/13	1.00	15 cm constant head; standing head (exterior outlet pipe height) was 2 cm higher
5	11/18	1.2*	17 cm constant head (adjusted 2 cm upwards on 11/13)
6	11/19	1.36	17 cm constant head
7	11/24	1.67*	*18 cm head (manually filled to check flow characteristics)
8	12/2	0.35	17 cm constant head
9	12/9	0.7	17 cm constant head
`0	12/10	1.5*	17 cm head; after cleaning

Table 3. Water test results

	Test Date/time	Submit Date/time	pH (lab)	NTU	Fe (mg/L)	*E. coli* (per 100ml)	Total Col. (/100ml)
CDWQS	--	--	6.5-8.5	5	0.3	0	0
1 (exp)	5-Nov-15	5-Nov-15 1 pm	9.1	27.6	1.13	170	TNTC
1 (control)	5-Nov-15	5-Nov-15 1 pm	8.7	34.6	1.36	55	TNTC
2 (exp)	11-Nov-15	11-Nov-15 1 pm	8.3	21.1	0.59	**0**	163
2 (control)	11-Nov-15	11-Nov-15 1 pm	8.8	35.8	0.79	**0**	TNTC
3 (exp)	19-Nov-15	19-Nov-15 1 pm	7.9	10.1	0.14	15	147
3 (control)	19-Nov-15	19-Nov-15 1 pm	8.4	21.8	0.74	62	TNTC
4 (exp)	3-Dec-15	3-Dec-15 1pm	7.6	2.18	0.27	**4**	55
4 (control)	3-Dec-15	3-Dec-15 1pm	7.9	15.9	1.07	140	TNTC
5 (exp)	10-Dec-15	10-Dec-15 1pm	**8**	5.54	0.54	23	80
5 (control)	10-Dec-15	10-Dec-15 1pm	8.6	16.6	1.02	25	TNTC

Notes

- TDS testing was not available
- Arsenic detection level = 1.6 ppb, all samples were below the detection level. CDWQS standard is 50 ppb.
- TNTC = >300 colonies
- CDWQS = Cambodian Drinking Water Quality Standards (2004)

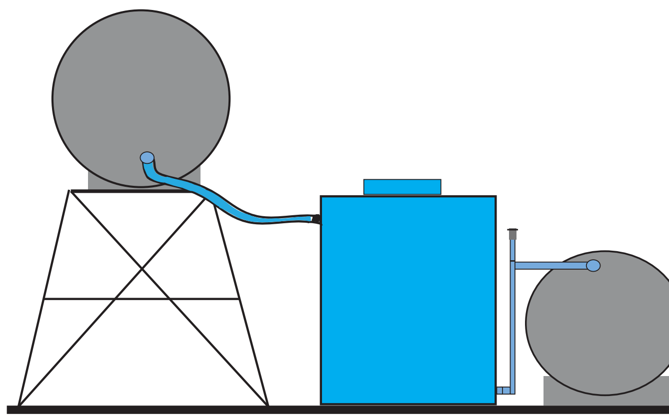
Table 4. Summary of change in experimental BSF water quality versus control

Date	**Turbidity**	***E. coli***	**Total Coliform**
Nov 5	Decreased 20.2%	Increased 67.7%	No change
Nov 11	Decreased 41.1 %	N/A	Decreased 45.7%
Nov 19	Decreased 53.7%	Decreased 75.8%	Decreased 51.0%
Dec 3	Decreased 86.3%	Decreased 97.1%	Decreased 81.7%
Dec 10	Decreased 66.9%	Decreased 8%	Decreased 73.3%

Large Biosand Filter Construction Manual

Community-scale
700-liter tank design

Version 1



Prepared for Trailblazer Foundation
Siem Reap, Cambodia

Prepared by Jason Hahn
University of Alaska, Anchorage
January 2016

Table of Contents

1. Introduction

The 3-tank large biosand filter in this desing uses a 700-liter BSF tank. The target output of this tank is 1.8 liters per minute, or 108 liters per hour. If run 12 hours per day, this BSF will 1,300 liters per day of filtered water.

Important considerations

The tank can operate continuously, and it can also pause between fillings. However, pause periods **should not exceed 48 hours.**

The filter is designed to operate under a continuous filration rate of **0.2 m^3/m^2/hour**. For this design, that is a continous (maximum) flow rate of **1.8 liters/min**. This flow rate is for **this design only**. The use of a different sized BSF tank or sand layers will require different calculations, and a different flow rate.

The filter is fed by gravity from a 1500-liter elevated storage tank. This tank will need to be filled using a gas-powered or human-powered pump.

After installation, it is important that the BSF tank is allowed to mature for 2-3 weeks while water flows through it before the users drink the water. This allows the biolayer to properly mature so that it can properly purify the water.

The biolayer will need to be cleaned regularly as it becomes clogged. This is important for proper function.

The details of who maintains the filter, or operates the pump, or distributes the water needs to be decided by the communities, and is beyong the scope of this construction manual.

Disclaimer

This is only a guide for construction. This manual does not guarantee that the biosand filter will produce water for safe human consumption. It is the duty of the implementing organization to test water samples and ensure the safety of water before installation.

2. Materials and supplies

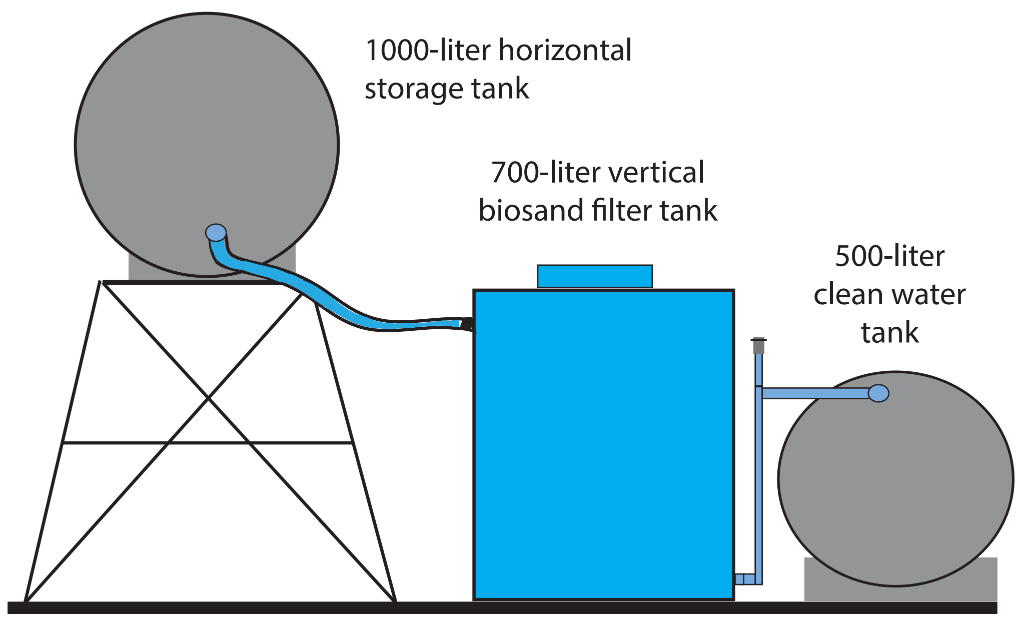
2.1 Water tank overview

This 700L Biosand Filter system is a 3 tank system comprised of 3 major tanks:

1) 1500-liter horizontal "dirty water" storage tank
2) 700-liter vertical biosand filter tank
3) 1000-liter horizontal clean water storage tank

All tanks should be *non-toxic, heat insulated, impact resistant, food-grade polyethylene tanks,* which are the standard water tanks available in Cambodia and most of the world.

3-tank system overview



Platform dimensions: Height = 1.5 m; top = 1.3 m x 1.3 m; bottom = 1.5 m x 1.5 m

2.2 BSF Water tank

All calculations, materials and measurements for this design are based on using a ***standard 700-liter PVC water tank*** with the following dimensions, so it is ***very important*** that only this type of tank is used. The use of a tank with different volumen or dimensions (height and diameter) will require a completely different construction manual.

The most important dimensions are:

1. Height of widest points (see diagram 1)
   = 1.35 meters

2. Diameter = 0.85 meter

3. Outlet hole:
   Diameter: 25 mm
   Location: 7 cm from bottom tank
   (measuring to center of hole)

Diagram 3. Outlet hole at bottom

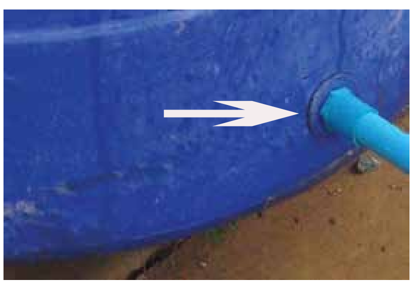
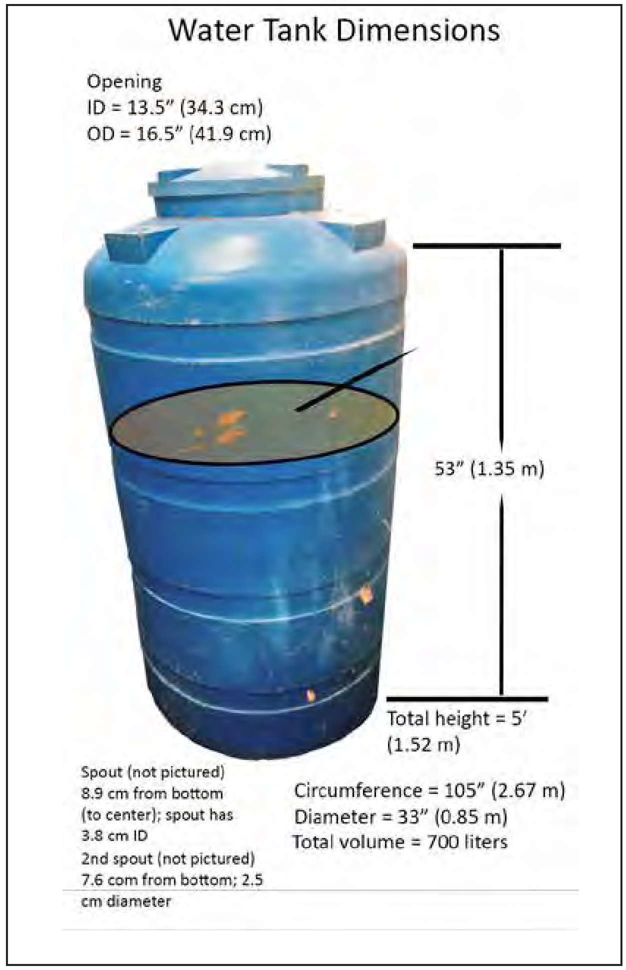


Diagram 2. 700L PVC water tank



If the tank does not come with an outlet hole at the bottom, this will need be drilled in before construction. The size of the tank lid at the top is not important, but it should be large enough to pour in sand and gravel and allow for cleaning.

2.3 Clean water tank

The clean water tank should have a 25 mm threaded inlet hole near the top of the tank. This hole needs to be 102 cm from the bottom of the tank.

If the tank does not have an inlet hole, one can be drilled as needed.

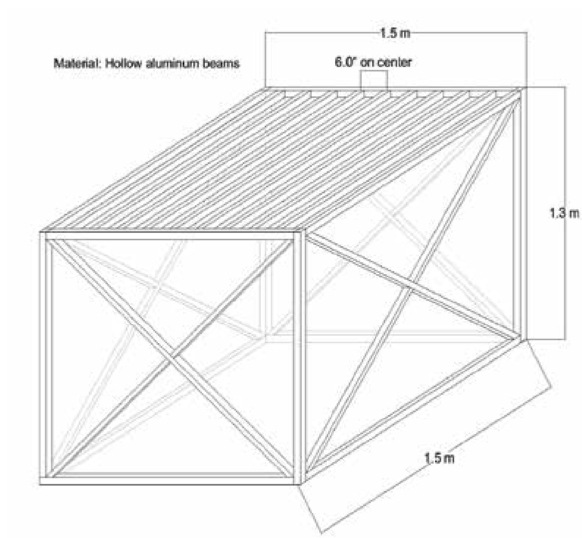
2.4 Storage tank

The 1500-liter storage tank is placed on an elevated platform to allow for gravity feeding into the BSF tank. The tank needs to have a lid at the top and an outlet hole at a bottom corner of the tank.

2.5 Storage tank platform

The storage tank platform should be constructed out of lightweight galvanized steel or aluminum. It needs to be strong enought to hold a full tank weighing approximately 1550 kg. The platform is a cube design with the following specifications:

1. Square base that is 1.5 m on each side
2. Square top that is 1.5 m on each side
3. Support cross-beams on the top to support the tank
4. Crossbeams on each side for additional support
5. Height is 1.3 meters



2.6 Sand and gravel

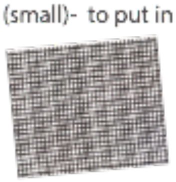
The optimal sand to use is 0.6 crushed rock sand that is prepared by Clear Cambodia. This comes in 25 kg bags, and should be available at Water for Cambodia in Siem Reap.

For the 700L BSF tank you will need 410 liters of crushed rock, which will be approximately 18 bags that weight 25 kg each. If this crushed rock is available, use the same washed river sand that is used for normal BSFs.

For gravel, you will need approximatley 50 of the 3.25L bags of small gravel (0.7 mm- 6 mm). During installation, you will dump the bags up to the 20 cm mark, and will use as many as needed.

2.7 Parts and Tools

PVC Part name	***# needed***
PVC pipe (25 mm)	**0.5 meter** (to be cut as needed)
PCV (20 mm 	**3 meters** (to be cut as needed)
Male adapter (25 mm) x 	2
Female connector (20 mm) 	2
Reducer (25 > 20 mm) 	1
Elbow 45 degree coupling (20 mm) 	7
Ball valve (20 mm) 	3
Male barb adapter 	1
T connector (20 mm) 	2
Male elbow adapter (20 mm) 	2
Elbow 90 degree coupling (20 mm) 	2

Misc part name	*# needed*
PE tubing (25 mm) 	3 meters (to be cut as needed)
Hose clamps x	6
Gasket (18 mm) 	3
Float valve (brass toilet) 	1
Empty washed oil can 	1
Filter (cloth) – small piece to put in air valve	
Mesh screen (small)- to put in PE tubing 	
PVC Pipe tape	
PVC glue	

Needed Tools

Hand band saw

Screwdriver

Box cutter knife (razor blade)

Drill
(IMPORTANT you do not have a chordless drill you will need to bring a small generator)

Drill bit- 22 mm

Crescent wrench

Water pump with plenty of 2" intake hose and outlet hose

3. Pre-installation preparation

The instructions in section 3 will describe all of the things that can be done to prepare the tanks. This can be performed at Trailblazer before going into the field.

3.1 Tank preparation

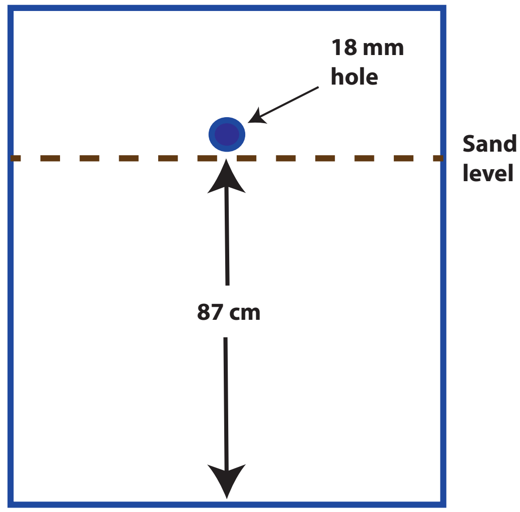
Drill cleaning valve hole.

The cleaning valve will be at the top of the sand level. This valve is used for cleaning the biolayer. It will drain the dirty water after swirling.

The sand level is at **97 cm** from the botton of the tank (77 cm sand + 20 cm gravel). The cleaning valve will be put at the top of the sand level.

Measure from the ground and up **97 cm**. Make a mark. ***Drill an 18 mm hole so that the bottom of the hole is at the mark.***

The drilled cleaning valve hole

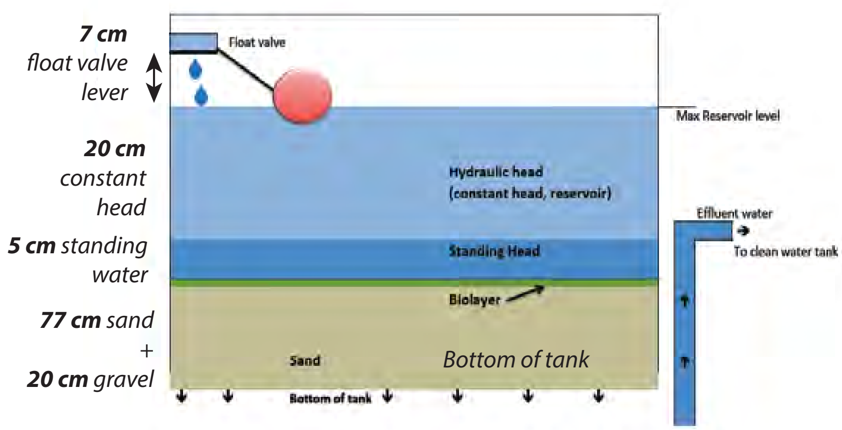


Drill float valve hole.

1) Determine the height of the float valve hole. This is determined by all of the measurements in the diagram on the right.

All of these add up to **129 cm**.

Measure 129 cm from bottom of tank. Make a mark. ***Drill an 18 mm hole so that the bottom of the hole is at the mark.***



3.2 Preparing the float valve

Once the float valve hole has been drilled, the float valve can be put into an empty tank for testing.

First, the splash guard must be constructed.

Instructions:

1. Find an empty regular small plastic oil can. Wash it very well with soap.

2. Using a box cutter (razor), cut out the splash guard piece like this:

Drill float valve hole here.

3. Drill an 18 mm hole. This will go onto the float valve inlet.

4. Drill 15-20 holes into bottom of splash guard to allow water to flow through.

5. Before taking to the installation site, install the float valve to test for proper flow.

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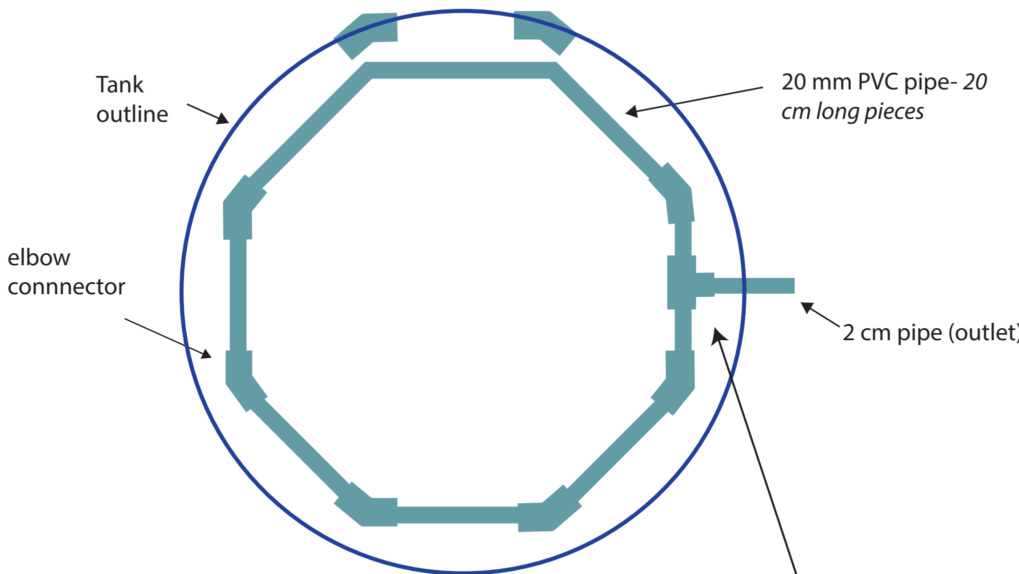
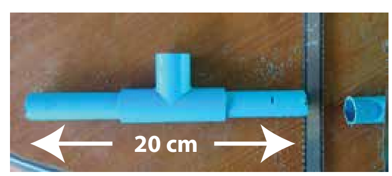
3.3 Preparing the drainage tube

Before going the the field, the drainage pipe can be constructed.
Diagram of drainage pipe to be put at bottom of tank:



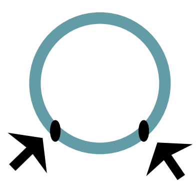
Instructions:

1. Cut 7 pieces of 20 mm PVC pipe to 20 cm long each.



2. For the outlet pipe connector, use one T-connector and 2 smaller pieces of PVC. Fit the PVC pieces into the T-connector and then measure so that the whole piece is 20 cm.

3. Drill Twelve 3.5mm holes in each section at 5 and 7 o' clock on the bottom of each pipe.



4. Glue the PVC pieces and elbows together so that the octagon is in **2 pieces.** During installation, these two pieces will be glued together inside the tank.

4. On-site installation

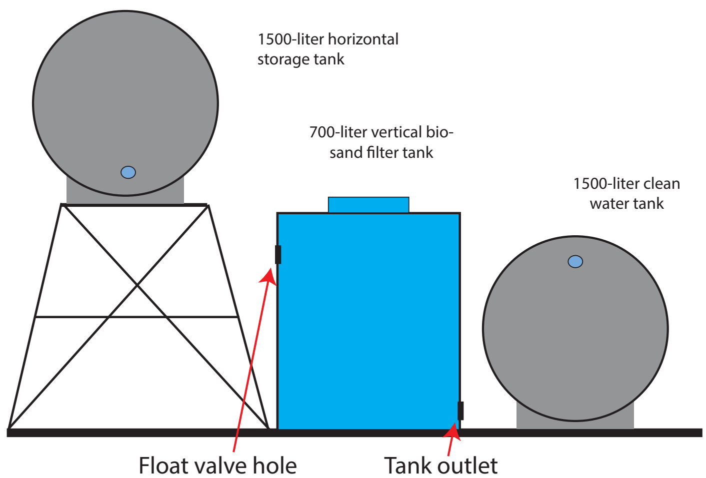
Bring all tools, materials and supplies listed in section 2.

1. Put metal platform on a flat surface. Put the storage tank on the platform.

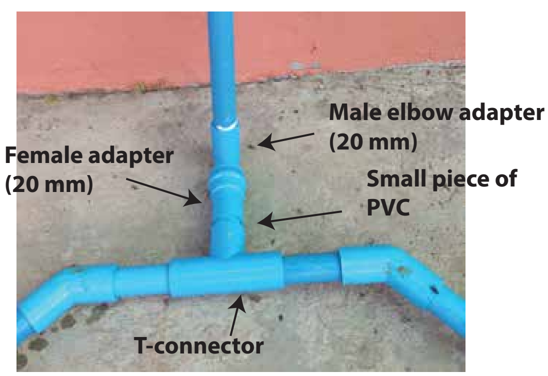
2. Put the BSF tank right next to the platform, so that the float valve hole is closest to the storage tank.

3. Place the clean water tank on a flat surface on the other side of the BSF tank.

All tanks should be less than 1 meter apart.



4.1 Drainage pipe installation



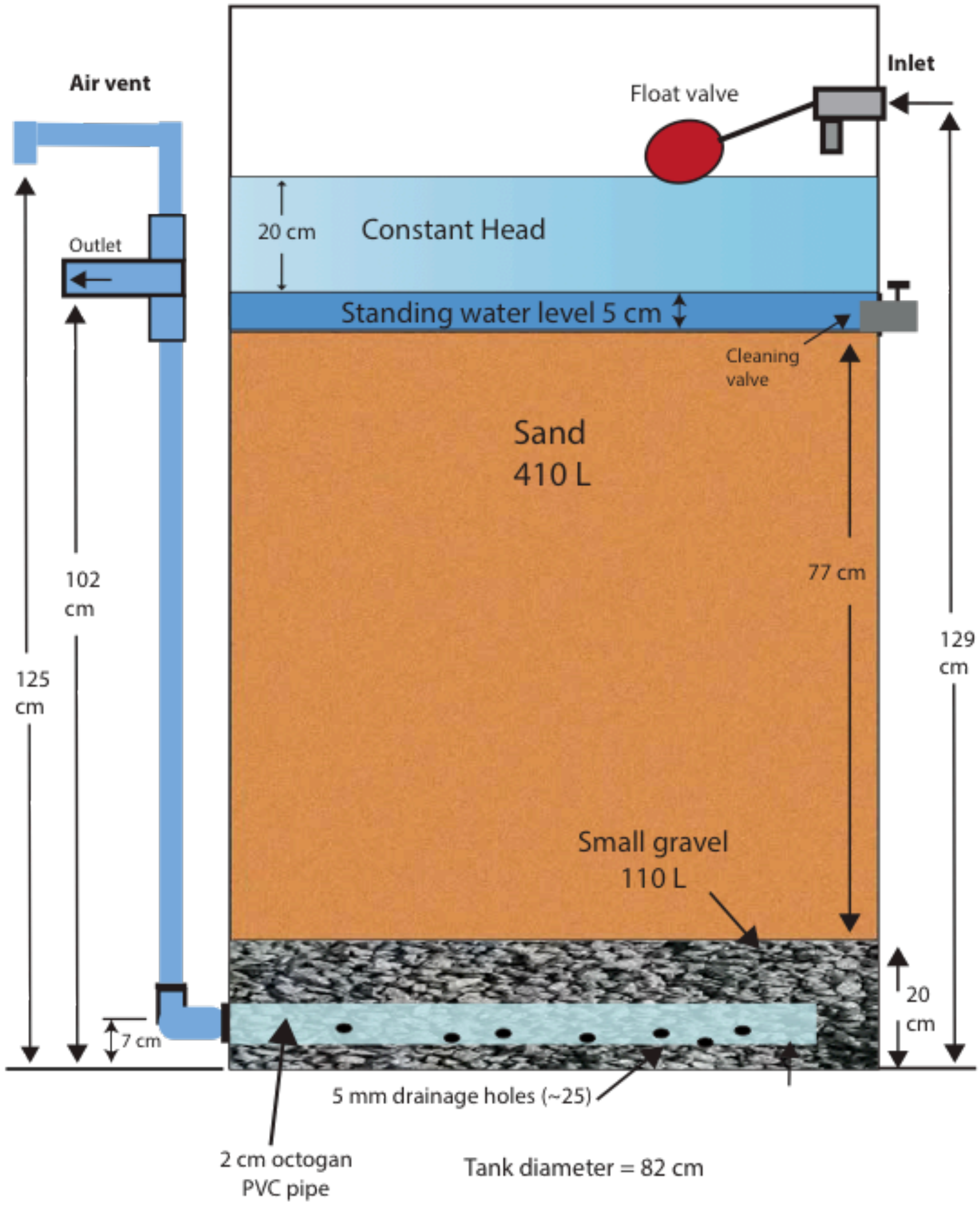
Inserting the half of the octogan drainage pipe into the bottom of the tank.

1. Place the two pieces of the octagon pipe onto the bottom of the tank. A small person may need to crawl into the tank to install this drainage pipe. Connect the two pieces together, with the T-connector facing the outlet hole. Make sure the small drainage holes in the pipes are facing towards the bottom of the tank.

2. On the outside of the tank, screw a male elbow adapter into the outlet hole near the bottom of the tank.

3. On the inside of the tank, screw the female adapter into the male adapter. Use a smale piece of PVC to connect the female adapter to the T-connector .

Diagram 1. 700-liter BSF tank



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4.2 Connecting the BSF tank outlet to the clean water tank

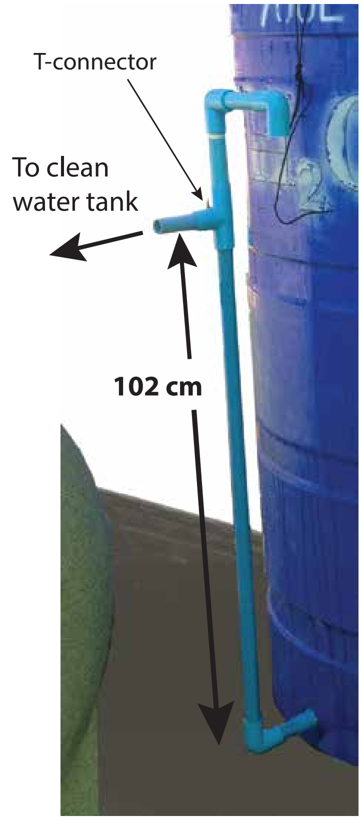
The outlet spout from the BSF tank delivers the filtered water from the bottom of the BSF tank to the clean water tank. The height of the BSF outlet spout determines the standing water level in the tank (see Diagram 1). For this 700-liter tank, the height of the spout is **102 cm from the ground**. This is measured from the ground to the bottom of the spout where it crosses to the clean water tank.

Instructions (also refer to Diagram 1)

1. Put a piece of 100-cm long 20 mm PVC into the male elbow at the bottom of the BSF tank (which was installed when the drainage tube was put in). Place a T-connector at the top of that PVC piece.

2. From the ground, measure up to the bottom of the T-connecter pipe (the piece going away from the tank). If this is longer than 102 cm, cut the PVC pipe so that it is 102 cm.

3. Screw a male elbow adapter into the clean water tank. Cut a piece of 20-mm PVC to connect the clean water tank to the T-connector on the BSF tank. Cut the PVC to the proper size.



Clean water tank

3. AIR VENT: Using 2 pieces of PVC and two elbow connectors, put an air vent on top of the T-connector. The air vent outlet should be 125 cm above the ground (it can be a few cm higher). Cut the PVC pieces to get this height.

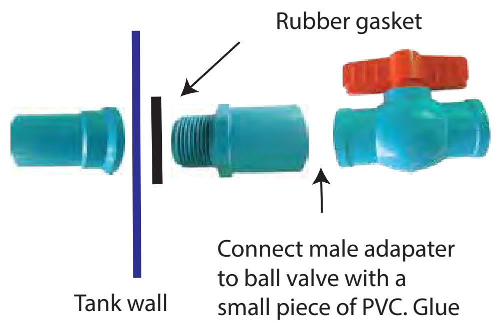
4. Place a small piece of cloth in the air vent to prevent insects and dirt from getting into the pipe.

IMPORTANT: The inlet to the clean water tank must be at the same height as the T-connector. The PVC should run straight across. The clean water tank may need to be raised a few centimeters to achieve this.

4.3 Installing the cleaning valve

Place a 20 mm female adapater on the inside of the cleaning valve hole

Screw the male adapter on the outside of the tank into the female adapter. Use a rubber gasket on the outside to seal the hole and prevent leaks.



Connect male adapater to ball valve with a small piece of PVC. Glue pieces together.

Close the ball valve before adding the media.

5. Adding media

5.1 Adding small gravel

On the outside of the tank, measure from the ground up 20 cm and make a line with a marker on the outside of the tank. Dump bags of small gravel into the tank until it reaches this line. This will take approximatley **110 liters** of small gravel.

5.2 Adding sand

1. First, fill the BSF tank about halfway full with water. Dump 25 kg bags of sand into the tank one at a time to the level of the drainage valve (97 cm).

2. Add water to fill the tank a few centimeters above the sand level. Use a hollow steel pipe and plunge into the sand to free trapped air bubbles and ensure full saturation of the sand.

3. If needed, add a little more sand to bring the level of sand to the bottom of the drainage valve (97 cm).

4. Use the drainage valve to drain out the water to the sand level.

5. Use the "sand leveling tool" (see photo on right) to make sure the sand level on the inside of the tank is even.

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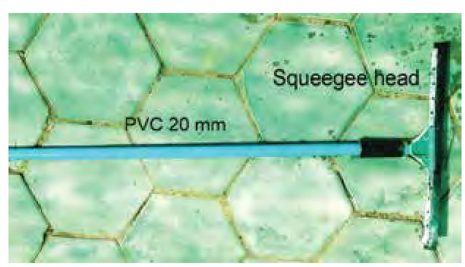
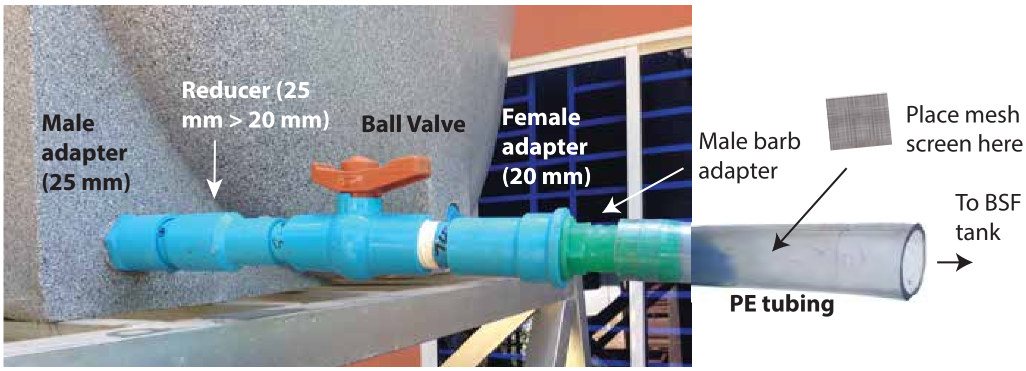
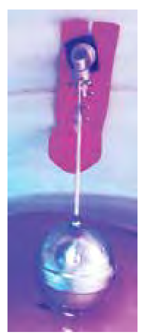


6. Hooking up the storage tank and float valve

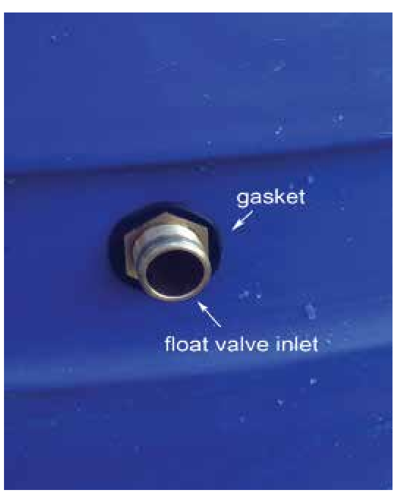
1. Screw a male adapter into the outlet hole at the bottom corner of the 1500-liter storage tank. (The tank should already be placed on the platform). Use the PVC parts below to make the connector for the PE tubing. Glue the pieces together. Connect 2 meters of PVC tubing to the male barb adapter at the end. Use hose clamps to secure the tubing. The PE tubing will connect to inlet valve of the BSF tank.

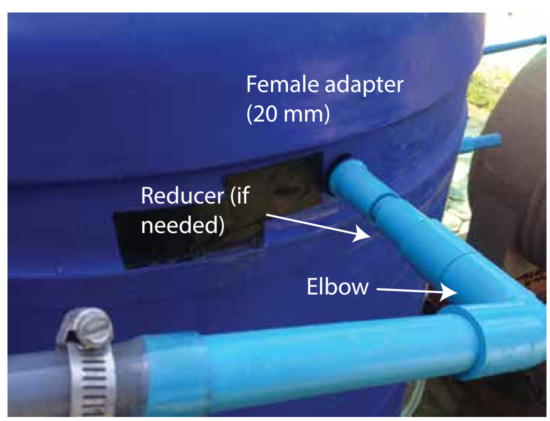


2. On the BSF tank, place the float valve on the inside of the tank. Place a rubber gasket between the float valve and the splash guard (see photo on the right). On the outside of the tank, put a gasket on the threaded valve inlet, and use a wrench to tighten the nut so that the float valve stays in place.



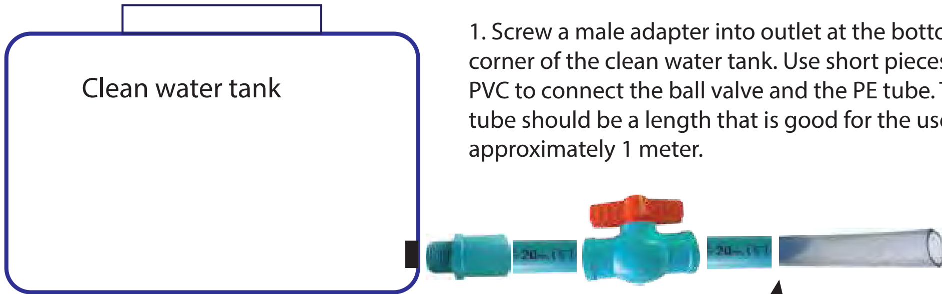
3. Screw a female adapter (20 mm) into the float valve inlet. Use pieces of PVC, elbows, and reducers as needed to connect the PE tubing from the storage tank to the BSF tank. Before connecting, put a small piece of mesh wire into the PE tubing (to prevent large particles from going into the float valve). Cut the PE tubing to the proper size so that it is as straight as possible. Use a hose clamp to secure it to the PVC fitting.





PE tubing (from storage tank)

7. Connecting the faucet to the clean water tank



1. Screw a male adapter into outlet at the bottom corner of the clean water tank. Use short pieces of PVC to connect the ball valve and the PE tube. The PE tube should be a length that is good for the user; approximately 1 meter.

8. Testing the float valve

1. With the ball valve on the storage tank in the off position, fill the storage tank using a water pump.

2. Mark a line on the outside of the tank 20 cm above the sand level. This is the **constant head level** (see Diagram 1). You can use the bottom of the drainage valve as a guide. This should be about 117 cm above the ground.

3. Turn the ball valve on, and let the water flow in until the float valve stops the flow. This should reach the 20 cm line that you marked on the tank. If this level is ABOVE or BELOW the 20 cm mark, bend the arm on the float valve so that it achieves this level.

4. Check the float valve for proper flow and that it is aligned properly on the inside of the tank.

5. Disconnect the PVC pipe going to the clean water tank from the T-connector. Let the water flow out (see picture on right).

Let water flow out during testing

8.1 Testing flow

1. Using a 1-liter bottle, test how fast water flows out of the BSF tank. The goal should be **2.25 liters/min**, which is 25% above the target flow of 1.8 liters/min. During the maturation of the tank, the flow will slow down.

2. If the flow is TOO FAST or TOO SLOW, bend the float valve arm to achieve 2.25 liters/min.

3. Let the flow continue for three full storage water tank loads (1500L each) while letting water drain to side.

4. **IMPORTANT:** It will take 2-3 weeks for the biolayer to mature. During this time the water should flow every day, but the user should not drink the water.

5. When this is complete, hook the BSF outlet back to the clean water tank and the system is ready for clean water use.

9. Final preparations

1. As water flows through the system, check for any leaks. Go back and check the pipe tape and use PVC glue any leaky pipes.

2. Check that the user has a method of filling the storage. Check the compatability of the user's pump system to fill the storage tank properly.

3. Check to make sure there are no other holes or openings in the system in which insects or small animals can crawl into the tanks.

4. Make sure that all of the tanks are secure and not able to tip over.

5. Make sure that there is a safe way for the user to climb onto the platform to fill the storage tank. If there is not, add a small ladder or other piece of equipment.

6. Make sure the user has tools to make small repairs: a screwdriver (for hose clamps), and a crescent wrench (for PVC fittings and nuts).

7. Ensure that there is a regular maintenance schedule and that the user can easily contact Trailblazer staff in case of problems.

10. User instructions

1. Instruct the user on how to turn off/on the ball valve for the storage tank. The valve should be off during storage tank filling, and left on during BSF flow.

2. Instruct the user to check the flow through the float valve. If it is clogged, the user should understand methods of cleaning the float valve.

3. Instruct the user to check the screen mesh in the tubing coming from the storage tank, to ensure it is not blocked.

4. Instruct the user on turning off/on the ball valve on the clean water storage tank. Make sure that the outlet hose from the clean water tank is stored so that it does not get dirty.

5. Instruct the user on regularly checking for flow. If flow is low, and none of the pipes or valves or clogged, it is time to clean the biolayer.

6. Instruct the user to make sure the lids on all the tanks stay securely shut. The lid of the storage tank should only be removed to add water.

7. Demonstrate to the user how to clean the biolayer (see next page).

11. Cleaning the biolayer

The biolayer needs to be cleaned regularly as it becomes clogged. A similar method is used as when cleaning a household BSF.

1. Let the water level go down to the standing water level.

2. Use a ladder or stool to access the top of the BSF. Remove the lid of the BSF during cleaning. Use a hand, or a small hand tool (like a spade) and perform the wet harrowing technique, while disturbing the biolayer as minimal as possible. During installation, instruct the user on how to perform the wet harrowing technique.

3. Once the water is very cloudy, open the drainage valve and let the dirty water flow into a bucket.

4. Open the storage tank valve, close the drainage valve and let more water flow into the BSF. It is okay for it to go higher than the standing water level. Repeat steps 2 and 3.

5. Once finished, close the drainage valve. Important: *Discard the dirty water into a place away from people. This is very dirty water full of pathogens. The user should wash their hands immediately after performing wet harrowing.*

6. Resume water flow through the tank.

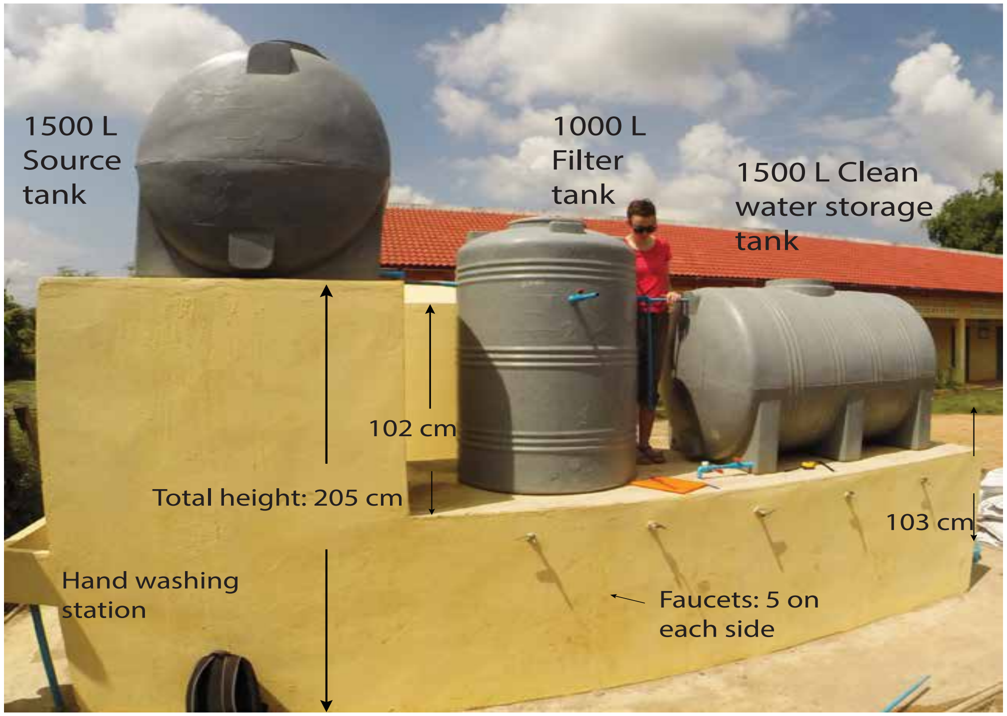
IMPORTANT: It will take the biolayer at least 2 weeks to regain function. *The user should not drink the water during this time.*

Appendix F: Svay Chek LBSF Installation Report

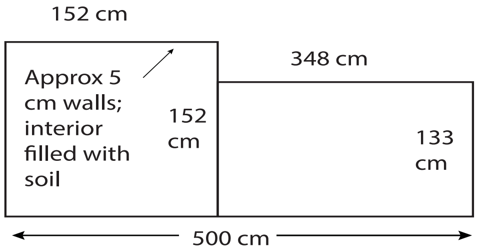
Field Observation notes
October 26, 2015
Community Biosand Filter Installation by Samaritan's Purse

Khvao Kaet Primary School
Svay Chek, Banteay Meanchey Province, Cambodia

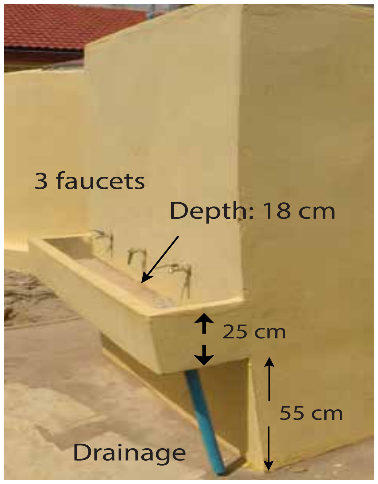
Water distribution center



Concrete platform dimensions



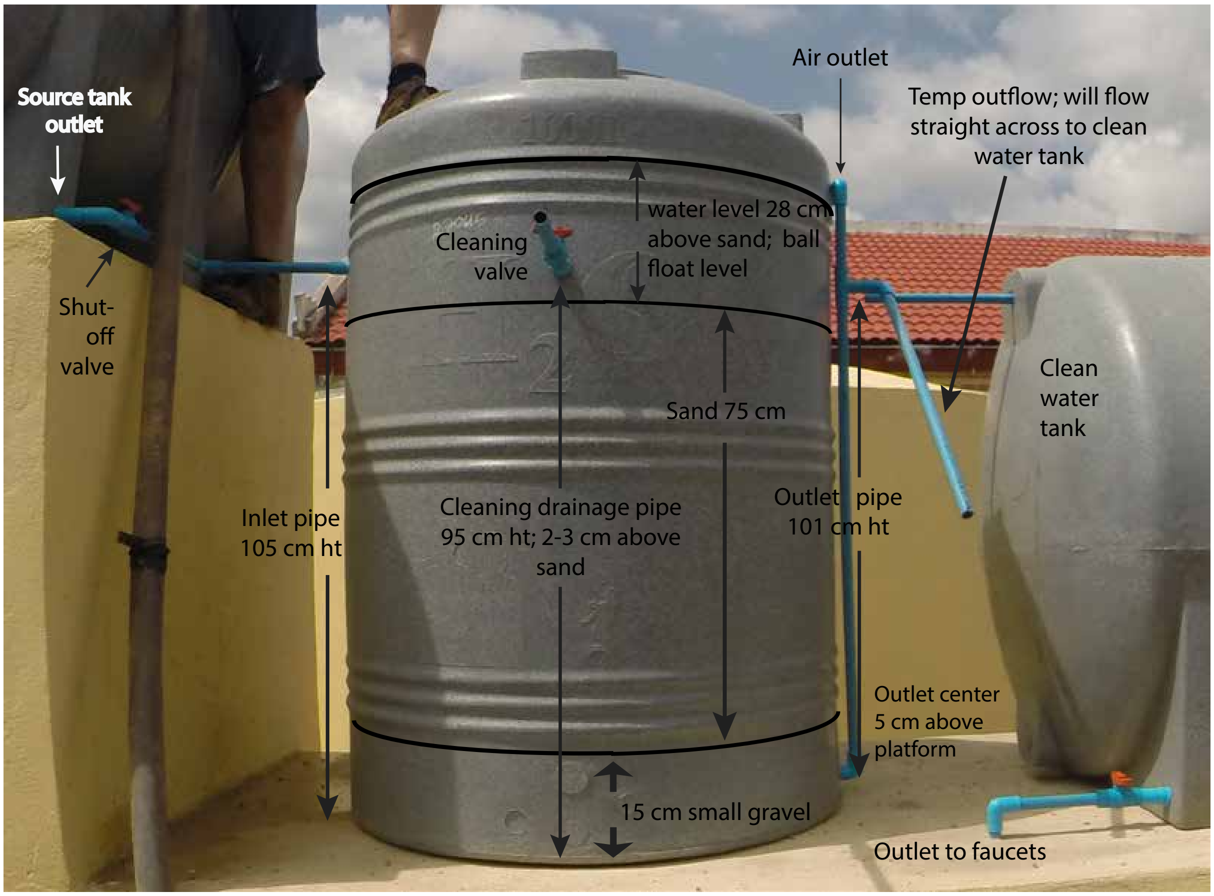
Handwashing station detail



Field Observation notes
October 26, 2015
Community Biosand Filter Installation; Samaritan's Purse

Elementary School
Svay Chek, Banteay Meanchey Province, Cambodia

Filter tank configuration

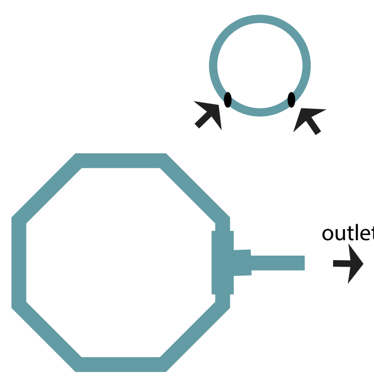


Sand
-0.6 mm crushed rock from Clear Cambodia
-20-25 kg bags
-Filled with 20 bags

PVC drainage tubes
-20 mm PVC pipe sections
-8 sections connected into octagan
-layed on bottom
-T-connection to outlet pipe

PVC tube cross section:
Twelve 3.5mm holes in each section at 5 and 7 o' clock

Float valve placement (pre-addition of sand)



Field Observation notes
October 26, 2015

Staff present

1. Samaritan's Purse: Vichet (lead), local BSF staff, several international volunteers
2. Trailblazer Foundation: Jason Hahn (volunteer), Rith Bony, Keo Vichet

Installation notes

1. Drainage octagon was placed into tank (See Figure 4)
2. Small gravel (0.7- 12 mm) was poured in up to 10 cm mark of tank
3. Tank was filled with water approx. half way
4. 25 kg bags of 0.6 mm crushed sand were poured into tank
5. Sand was poured up to a few cm below cleaning drainage tube (approx. 95 cm level); sand is *overfilled slightly* to compensate for compaction during settling
6. Water was added to fill tank
7. A hollow steel pole (approx. 5 cm diameter) was plunged into the sand to free trapped air bubbles and ensure full saturation of the sand
8. Water was topped up to 28 cm head above sand (23 cm below opening); total sand + water level = 123 cm
9. Float valve was installed at 105 cm, making it fully submerged
10. A string was connected from the float valve arm to the ball. The 28 cm head was now the shut-off point.
11. The filter tank outlet was NOT connected to clean water tank, it was allowed to drain off to the side
12. Flow was tested with the 28 cm head; found to be 3 L/ min at that point.
13. Continuous flow will be done for three full source water tank loads (1500L each) while letting water drain to side.
14. At that point, filter tank will be connected to clean water tank for operation.

Estimated cost

1. Approx $2000 dollars
2. Normally $100 donation to Samaritan's purse from school is required; for 3+ filter systems, a total $200 donation is required (as in this case)
3. Students are charged 500 riel per month (approx. $0.12 USD) to go towards maintenance fund of BSF system